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Fundamentals of Illumination

By
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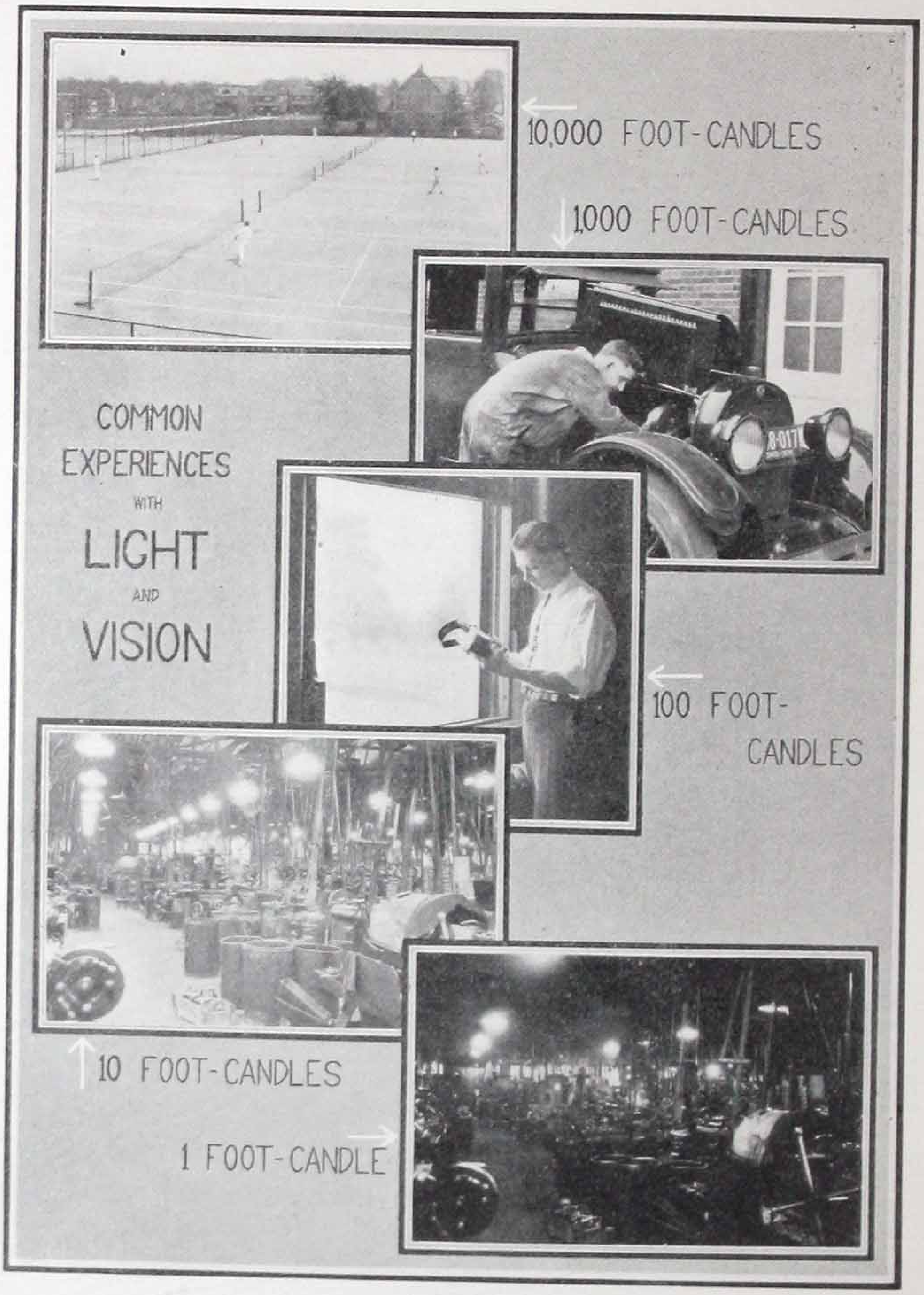

Even the best installations of artificial lighting provide much less illumination than the daylight under which the eye evolved.

Fundamentals of Illumination

INTRODUCTION*

LIGHT AND VISION

Nature of Light

Every one has seen the effect of light, yet relatively few have had occasion to study minutely its nature and how it is produced. Today it is generally accepted that light sources, which are usually substances at a very high temperature, send out waves which are similar to the waves utilized in radio communication except that they differ in length. Light waves range from 40 to 76 millionths of a centimeter while radio waves are more than a 100 million times as long, from 100 to 25,000 meters. Hot bodies send out many other waves beside those capable of producing vision, but the eye, like a radio receiver tuned for a narrow range, is unable to respond to energy of wave-lengths too long (invisible heat waves) or too short (ultra violet waves) to fall within the range of .000040 to .000076 centimeters. When these waves enter the eye, vision takes place. Light might be defined, therefore, as radiant energy in the form of a wave motion of such a range as to affect the eye and produce the sensation called vision.

Without light, the most important of the senses which bring information from the outside world—the sense of sight—is useless, for without light even a perfect eye is blind. On the other hand, the manner in which light is used, largely determines what kind of service our eyes are able to render, for it is quite possible that through bad lighting these delicate instruments of vision may become impaired and defective. If one shuts his eyes for a few seconds, he can easily realize how much his knowledge of what is going on in the world depends on light and, conversely, he needs only to look at the sun for an instant to realize how annoying and harmful a glaring light may be.

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*This introduction is taken from Chapters on Light, published by the Illuminating Engineering Society, for the use of schools and colleges.

The greatest of all our light sources is the sun. Even on a cloudy day when the sun is not "shining," the sky gives off light which it receives from the sun. At night a degree of illumination is produced by the moon and some of the other planets, not because they generate light, but because, while our half of the earth is turned away from the sun, they are still exposed to the sun's rays and reflect a very small portion of the sun's light to the earth.

The Process of Seeing

Look at a building upon which the sun is shining. Through the agency of light, its shape, form, size, and the color of its parts can be distinguished. The sun is pouring upon it a myriad of energy waves including the light waves which range in length from .000040 to .000076 centimeters. Instead of stopping or absorbing all the rays, each individual part of the building reflects and scatters a portion of the rays falling on it and absorbs the rest. As a result of this scattering, some light from all parts of the building in the field of view falls upon the eye; furthermore, the parts of the building all appear in their characteristic colors. The bricks, for example, appear yellow because in general they absorb relatively few of the rays of wave lengths which are capable of giving the impression yellow. The eye in turn conveys

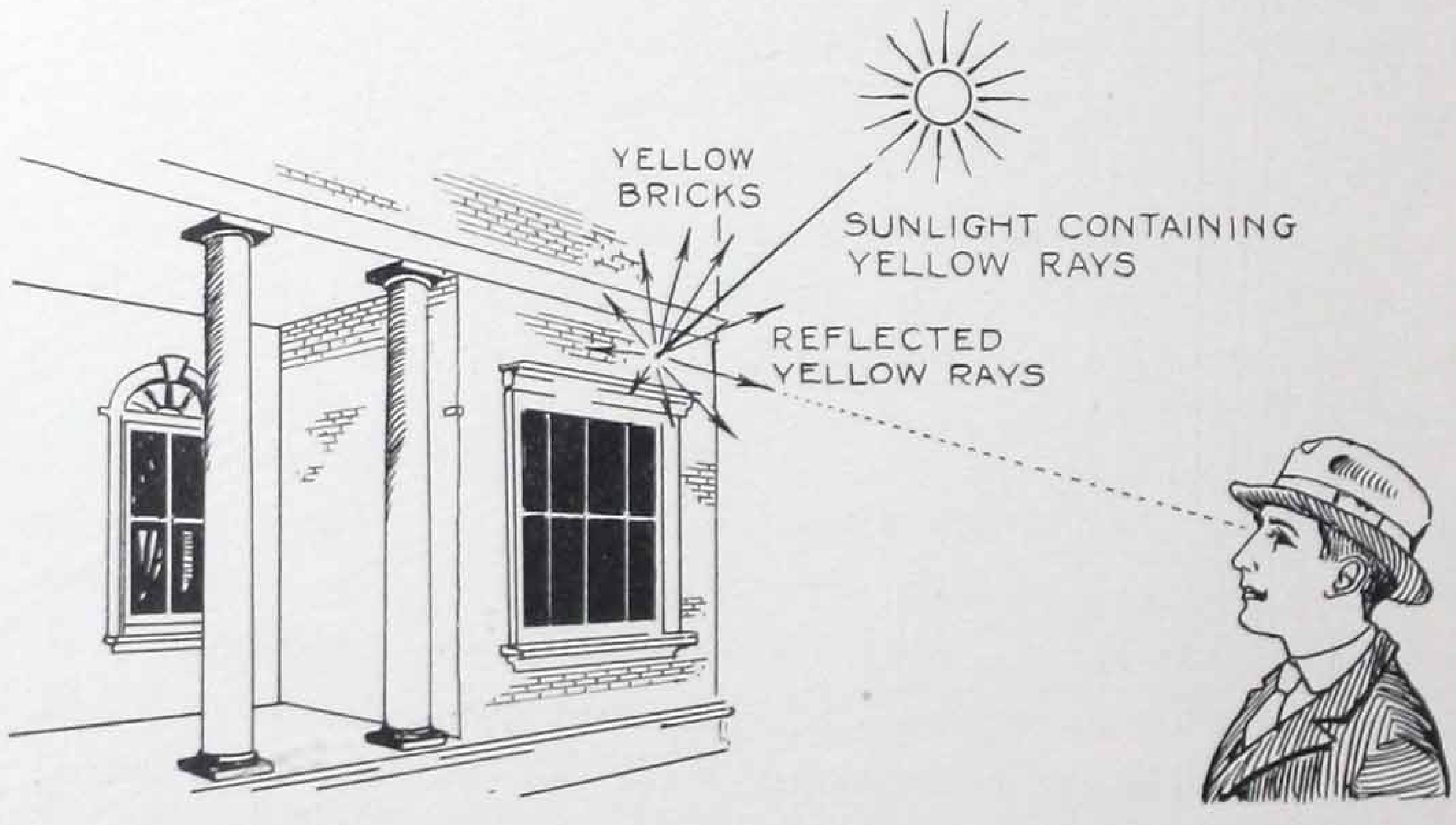


Fig. 1—Colored objects reflect principally rays corresponding to their colors.

the message to the brain that the bricks are yellow. In the same way, the brown mortar absorbs most rays except a particular combination of waves which make up the color brown and when these are reflected to the eye, they convey the impression that the mortar is brown. If there

are any parts of the building which absorb practically all of the sun's light that falls on them, with the result that no visual impression is made, those parts are called black. The white portions of the building reflect nearly all of the light that falls upon them, equally for all wave-lengths, and it is for this reason that the pillars appear white. The shape and form of the building and its parts are made evident by the varying amounts of light falling on the different surfaces and the percentage of this light which they reflect toward the eye. The pillars appear round only because the eye has become accustomed to recognize certain graduations of light and shade as being characteristic of round objects. Likewise, recesses in the wall are recognized as such because the parts that are in shadow do not receive as much light from the sun and therefore reflect correspondingly less to the eye.

This phenomenon of light and shade is used by the artist in making a black and white sketch of the building, where he uses no color but simply depicts, by the shading of lines, the amount of light each part of the building directs toward his eyes. The camera does the same thing with even greater exactness. Even a child can recognize these translations of the actual object to a flat surface which shows only the varying degrees of light reflected to the eye.

Again, the amount of light available has much to do with how much we see and how readily we see. For example, when examining the works of a watch, it is natural to move over to a window to get the maximum illumination. Likewise, in playing tennis in the late afternoon, the ball may be clearly visible when held in the opponent's hand but the light may be entirely inadequate to see the ball when in motion.

Such, then, is the process of seeing—a highly complicated one which the eyes are performing constantly. It is particularly important to remember that in both natural lighting and in artificial illumination an object is seen not as a result of the light which travels direct from the light source to the eye, but only as a result of the light which travels first from the source to the object looked at and thence to the eye.

Part I—Fundamental Concepts

Units of Measurement—The Candle

A generation or two ago when new light sources began to supersede the candle, it was most natural that the illuminating power of these new sources should be expressed in terms of the candle familiar to all. It is probable that the very first comparisons of two light sources were made by setting up the two lamps in the line of vision and gauging them by means of the eye, the most natural direction in which to look at the sources being the horizontal.

While there are an infinite number of directions from which the eye might look at a source, the light-giving power in a horizontal direction was made the basis of comparison, and the strength of the light in this direction from a candle made according to certain definite specifications, was arbitrarily chosen as the unit of intensity and called a *candle*. The newer illuminants as they were brought out, were rated according to their strength in this same direction and were stated to give so many candles, so that when a lamp gives 10 candles, it is meant that its intensity or strength in a horizontal direction is equal to ten times that of one standard candle. This rating of a lamp is made by means of an instrument known as a photometer, a description of which will follow later.

One essential point to remember in this connection is that the candlepower of a lamp represents the intensity in one direction only. In practice it has been customary for years to rotate the lamp about a vertical axis while the candlepower was being determined and the result was known as the mean or average horizontal candlepower.

To carry this conception of candlepower a little further, assume the conditions existing in Fig. 2. In *A*, on the left is a standard candle and on the right a photometer pointed toward the candle. From what has already been stated, it is obvious that when the photometer is balanced against a known source, it will indicate one candlepower. In *B*, the same candle is surrounded by a sphere painted a dead black so that none of the rays striking it are reflected but are absorbed and cease to be light—in other words, are thrown away as far as the experiment is concerned. In this case the photometer will still indicate a luminous

intensity of 1 candle in spite of the fact that a great deal of light has been thrown away. In *C*, a sphere with a much smaller opening is used and therefore still more of the light is wasted, but even in this case the photometer will indicate 1 candlepower. In fact, the reading will be 1

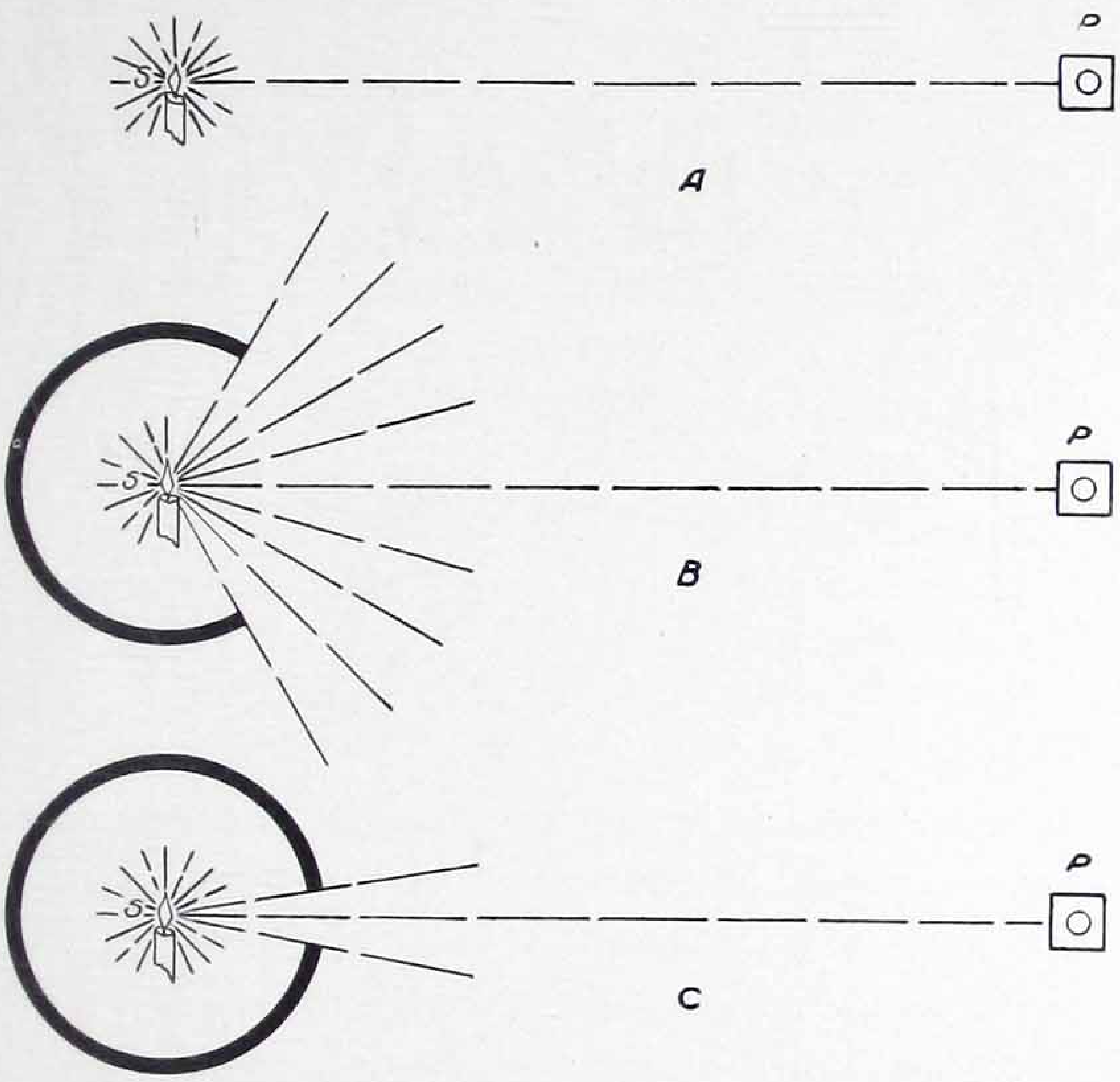
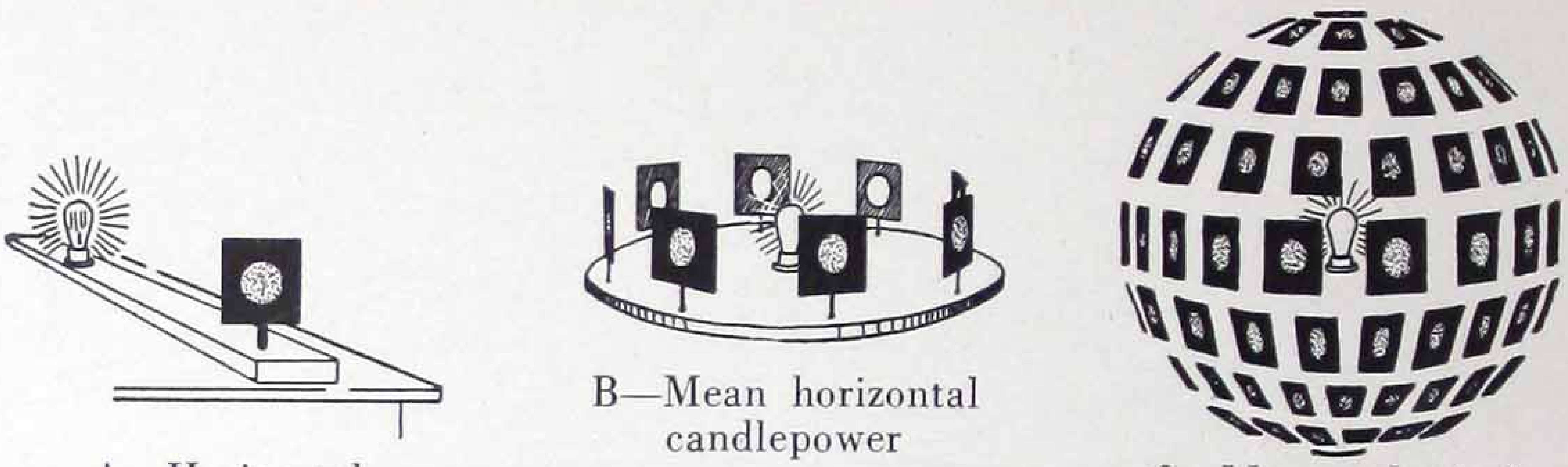


Fig. 2—The candlepower in the direction of the photometer is not changed by partially surrounding the light source with a non-reflecting surface.

candle regardless of the size of the opening, that is, regardless of the quantity of light allowed to be emitted, provided the direct rays from the candle to the photometer are not obstructed. The proverbial light hidden under a bushel, if it is 1 candle, will give out 1 candlepower if there is a small hole in the bushel for a beam to escape. As far as its general illuminating value is concerned, it is still "hidden under a bushel." This leads to the important conclusion that the candlepower of a source does not necessarily give an indication of the total quantity of light emitted by the source. An automobile headlamp may, for example, produce a beam with maximum candlepower of 100,000, the source being a 21 c-p lamp.

Closely related to candlepower is *mean spherical candlepower*. The mean spherical candlepower of a lamp is simply the average of all the candlepowers in all directions about the lamp. A source giving one candle in every direction would have a mean spherical candlepower of

1, or if a source gave off various candlepowers in different directions and if the average of all these candlepowers were 1, the source would have a mean spherical candlepower of 1. The infinite number of directions in which a source ordinarily emits light do not all lie in the



A—Horizontal candlepower

B—Mean horizontal candlepower

C—Mean spherical candlepower

Fig. 3—Measurement of candlepower.

same plane, but extend into space on all sides about the source, like the pricks of a chestnut burr.

The Lumen

Assume that a source is giving one candle in every direction, and that this source is placed at the center of a sphere painted black on the inside and having a radius of 1 foot, as shown in Fig. 4. *OR* represents an opening in the sphere through which some of the light may escape. The quantity of light allowed to escape may be varied by varying the size of the opening, with the candlepower of the source and the radius of the sphere remaining fixed; if some definite size of opening at *OR is assumed,* a definite quantity of light which may be used as a unit for measuring quantity will result. The simplest area or unit to assume for *OR* is 1 square foot, and it has been established that the amount of light escaping shall be considered the unit of quantity, and it is called a *lumen.** Thus a permanent unit for the measurement of the quantity of light has been established; the mathematical relations used to fix it serve only the same purpose as two scratches on a platinum-iridium bar in the International Bureau of Weights and Measures, the distance between which at a definite temperature is called a meter.

If the area of *OR* is doubled, the light escaping will be 2 lumens; if the area of *OR* is made 1/4 square foot, the light escaping will amount to 1/4 lumen. On the other hand, if there is a source of 2 candles,

*A sphere of any radius might be chosen as long as the proportion is kept the same, i. e., making the size of the opening such that its area would be equal to the square of the radius. The quantity escaping would still be one lumen.

2 lumens will be emitted through an opening of 1 square foot in this particular sphere. Since the total surface of the sphere having a radius of 1 foot is 12.57 square feet,† removing the sphere entirely, there would be the equivalent of 12.57 openings the size of *OR*; that is, if the candle gives 1 candlepower in every direction, with the sphere removed it would give 12.57 lumens. This means that if the mean spherical candlepower of a lamp is known, multiplying this value by 12.57 gives the number of lumens emitted by the lamp. A value of 12½ is sufficiently accurate for most practical purposes, and is a convenient figure; dividing the mean spherical candlepower by 8 and multiplying by 100, the lumen output is obtained directly.

A lumen may also be defined as being equivalent to the quantity of light intercepted by a surface of 1 square foot, every point of which is at a distance of 1 foot from a source of 1 candle. (Fig. 4B.)

While the foregoing definitions establish the quantity of light used as the basic unit, it must be remembered that a lumen, in order to be a lumen, need not necessarily conform with these specifications if the

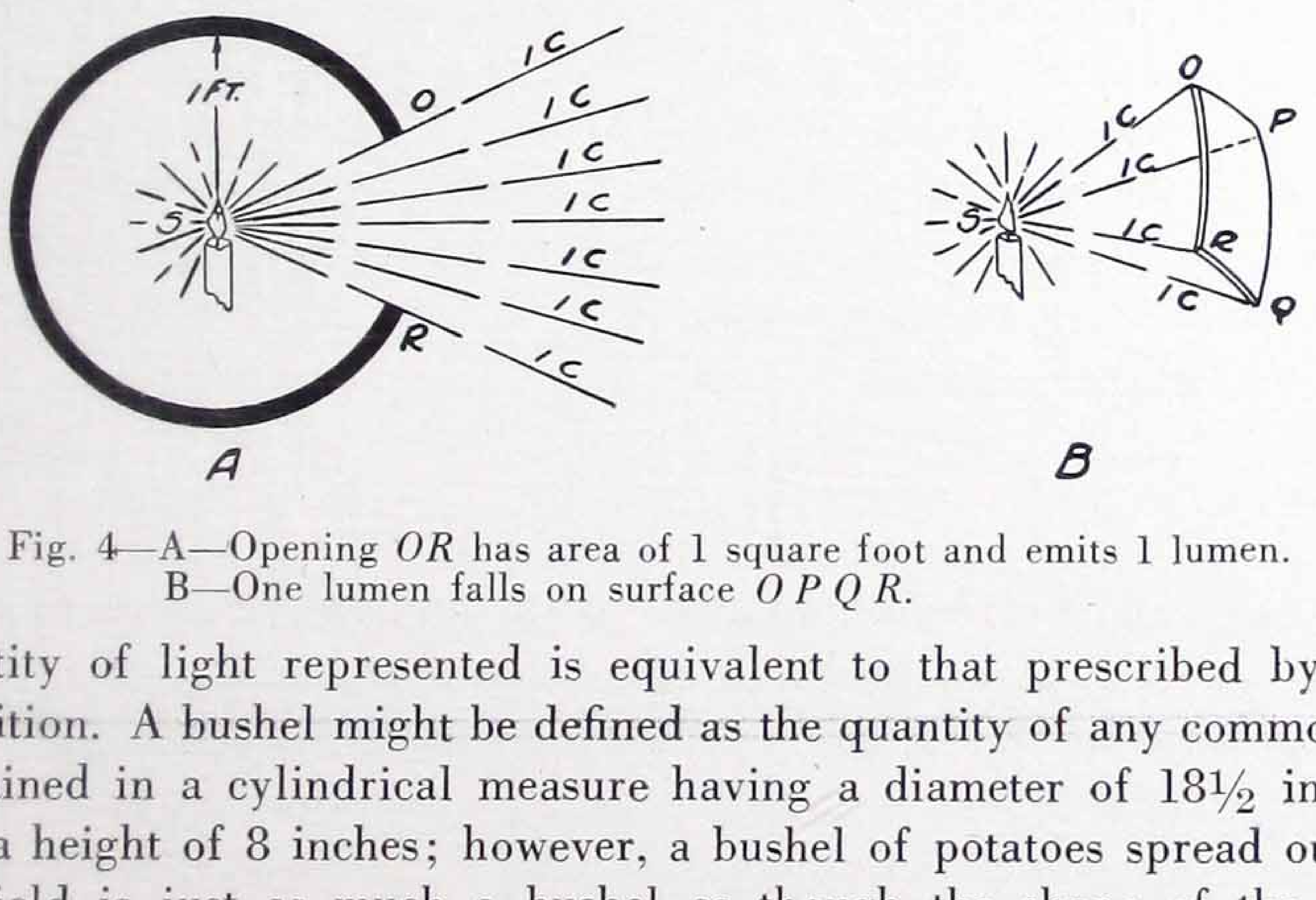


Fig. 4—A—Opening *OR* has area of 1 square foot and emits 1 lumen.
B—One lumen falls on surface *O P Q R*.

quantity of light represented is equivalent to that prescribed by the definition. A bushel might be defined as the quantity of any commodity contained in a cylindrical measure having a diameter of 18½ inches and a height of 8 inches; however, a bushel of potatoes spread out in the field is just as much a bushel as though the shape of the pile conformed in every respect to the dimensions mentioned.

The Foot-Candle

Light is a cause and illumination the effect or result. Both the lumen and the candle are used to measure the cause, these units

†The surface of a sphere is equal to the radius squared, multiplied by 4 x 3.1416.

applying to the light source itself and not to the point where the light is utilized. To measure the illumination on a newspaper, desk, or other working plane, there is a unit called the *foot-candle.* A foot-candle represents an amount of illumination equal to that produced at a point on a plane 1 foot distant from a source of 1 candle and perpendicular to the light rays at that point. In Fig. 5, if the source S gives an intensity of 1 candle along the line SA and if A is 1 foot distant from the source, the level of illumination on the plane CD at the point A is 1 foot-candle.* The level of illumination measured in foot-candles, is the measurement most intimately associated with everyday use of light, and a measurement which the eye either consciously or unconsciously is making whenever the faculty of vision is being employed, for the number of foot-candles there are on the working plane, other things being equal, determines directly whether or not there is sufficient light. A working idea of a foot-candle of illumination may be obtained by reading a newspaper for ten minutes with the paper held approximately one foot away from a candle. At first the illumination may seem adequate but the observer soon wishes for more light.

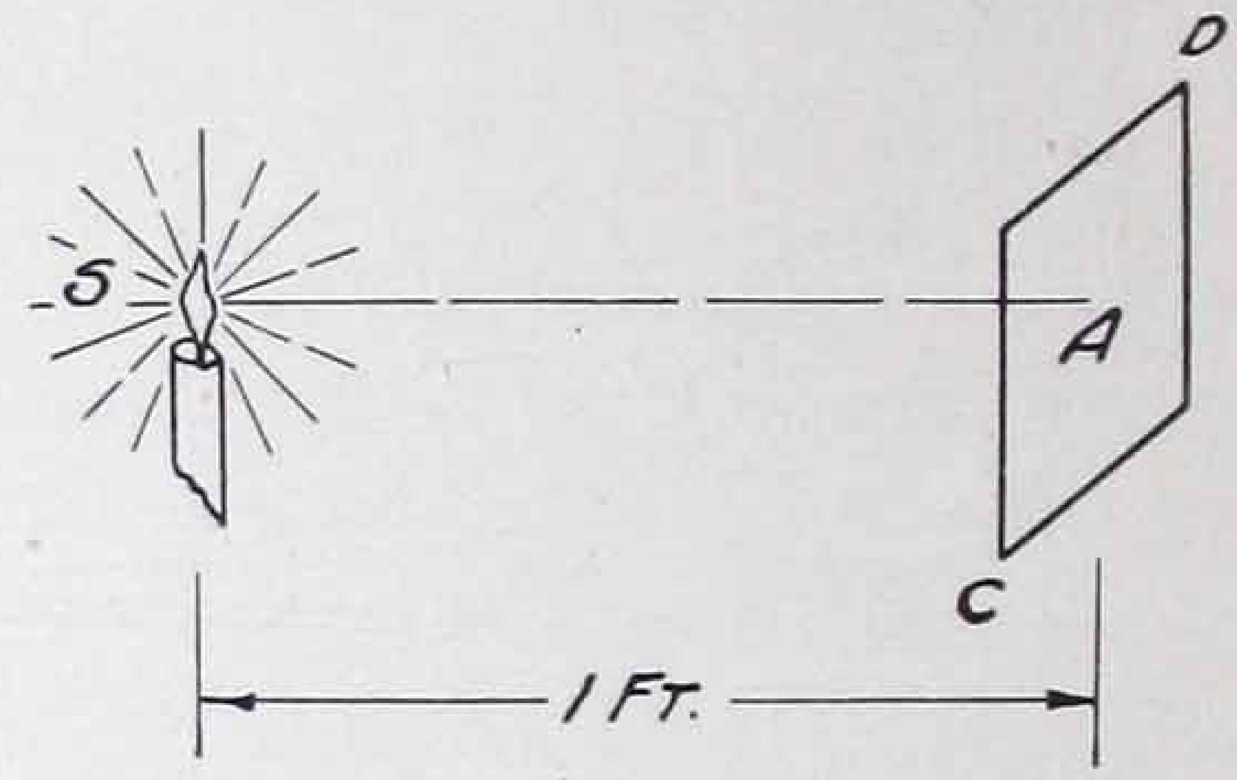


Fig. 5—The illumination at A is 1 foot-candle

Care should be taken to avoid confusing the amount of illumination on a surface, as indicated by the foot-candles, with the appearance as

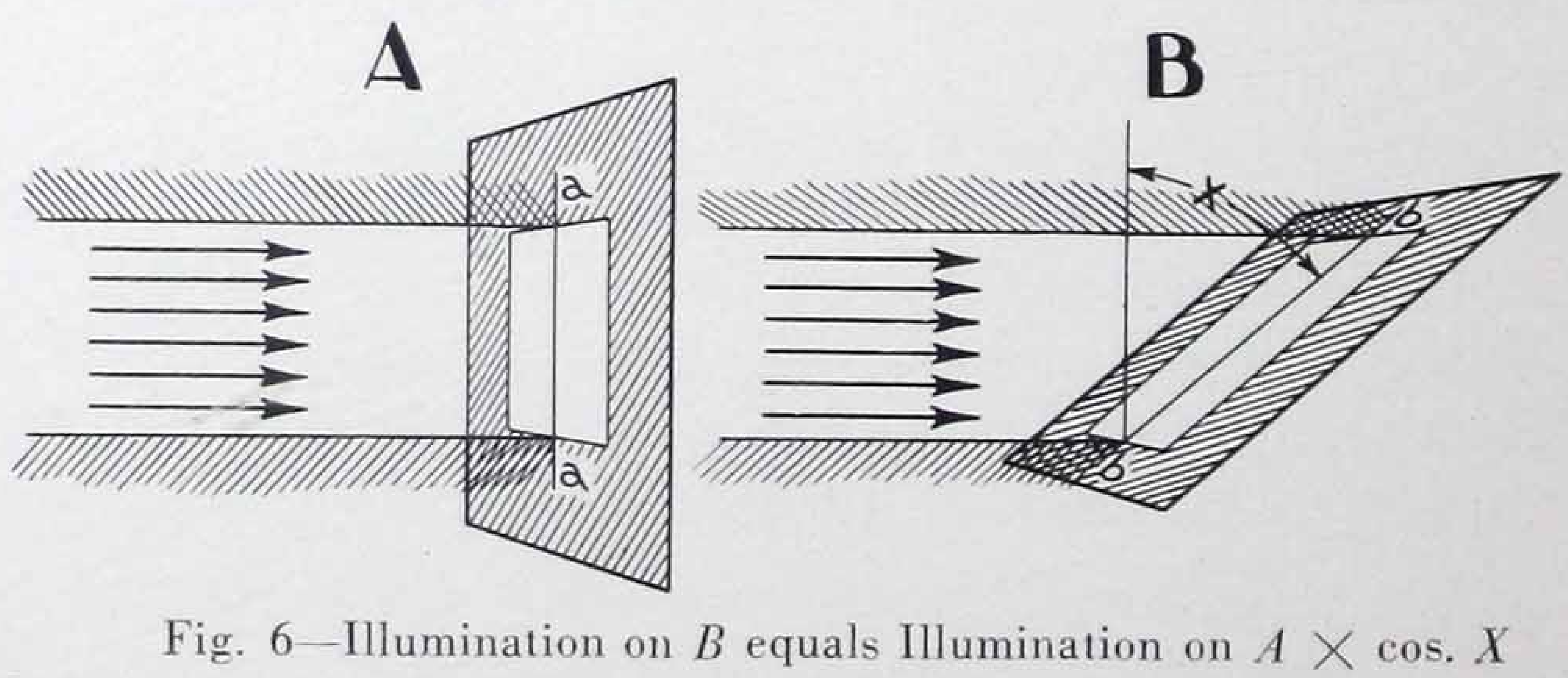


Fig. 6—Illumination on B equals Illumination on $A \times$ cos. X

*If instead of being perpendicular to the beam of light a plane is tilted at the angle X, as shown above, the same amount of light is spread over a greater area. The illumination on B is to A inversely as the length bb is to aa or as cosine X. Thus if cos X=.7, and the footcandlage on A is 1, the illumination on B would be .7 foot-candles.

regards brightness of the surface. A gray surface lighted to an average of one foot-candle will not appear as bright as a white one, for a greater proportion of the light falling upon the surface is absorbed and lost. The brightness of an object depends upon both the intensity of illumination on it and the percentage of light that it reflects.

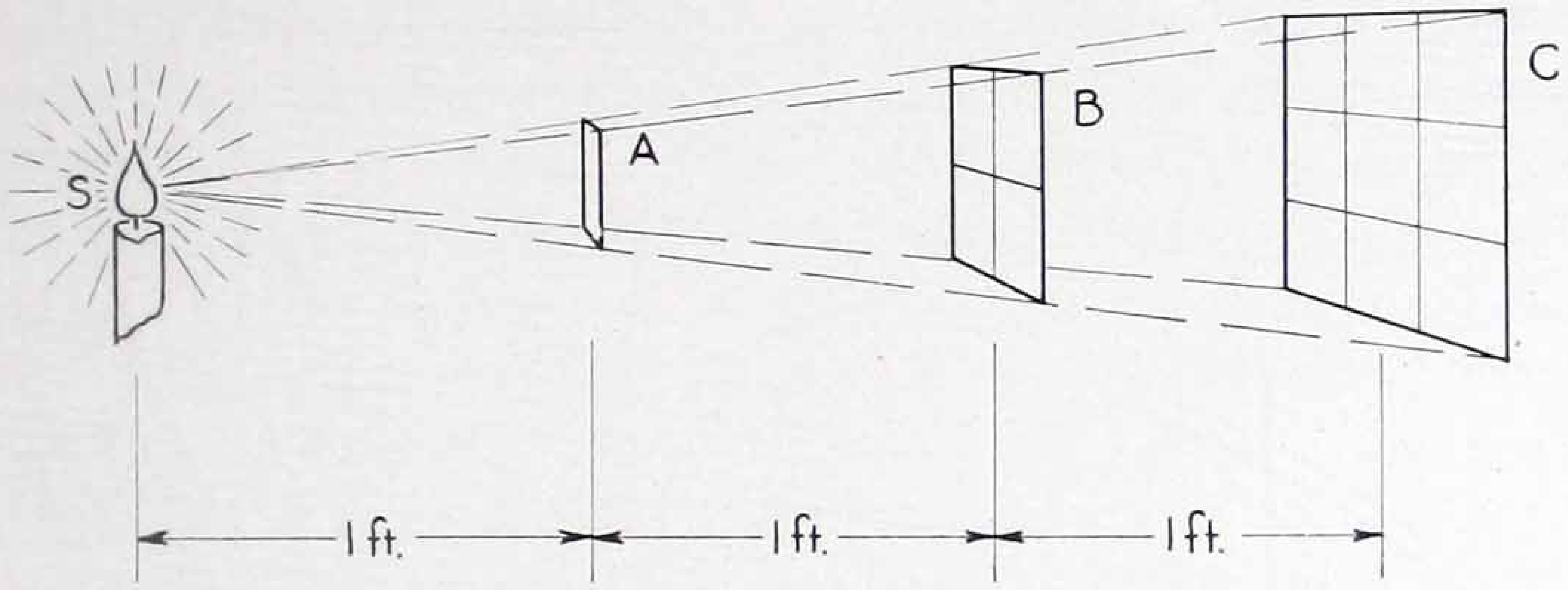


Fig. 7—The illumination on a surface varies inversely as the square of the distance from the source to the surface.

Since the facility with which objects can be seen depends upon the amount of light they reflect, high levels of illumination must be provided where the materials worked upon are dark in color. The ratio between the foot-candles reflected from a surface and the foot-candles directed on it is called the reflection factor of the surface. The following table shows the reflection factors of a number of painted surfaces.

Table I—Reflection Factors

White	80%	Sky Blue	35%
Ivory	70%	Olive Green	20%
Buff	65%	Cardinal Red	20%
Sage Green	40%	Black	5%

Having defined the foot-candle as a unit of level of illumination, the next point of interest is in seeing how the foot-candles of illumination vary as the candlepower of the source varies, and also as the distance of the plane from the source varies. It is obvious that if in Fig. 5 instead of an intensity of 1 candle along the line *SA* there is an intensity of 2 candles, the illumination at *A* would be twice as great, and if there is an intensity of 5 candles the illumination at *A* will be five times as great. With a source of 1 candle as shown in Fig. 7, the intensity of illumination on A, which is 1 foot distant, is 1 foot-candle. If, however, the plane A is removed and the same beam of light that formerly was intercepted by A is allowed to pass on to the plane B, 2 feet away, this same beam of light would have to cover four times the area of A,

and the average illumination on B, 2 feet away, would be one-fourth as great as that on A, 1 foot away, or one-fourth of a foot-candle. In the same way, if B also is removed and the same beam allowed to fall upon plane C, 3 feet away from the source, it will be spread over an area nine times as great as A, and so on; at a distance of 5 feet there would be only one-twenty-fifth of a foot-candle. From this it may be concluded that the illumination falls off not in proportion to the distance, but in proportion to the square of the distance. This relation is commonly known as the *inverse square law.*

The inverse square law is the most widely known of all optical laws. Its misapplication has led to many poor lighting installations. In these, the principal error has been in mounting the luminaires too low, with the idea of getting more footcandlage on the objects to be looked at. Mounting a local lighting unit close to the work is entirely correct if the area to be lighted is small, such as in lighting the toolpoint of a lathe or the needle of a sewing machine, but in no case should luminaires of a general lighting system be lowered to accommodate the apparent need for more light over a particular point.

The distribution curve of a luminaire for general lighting will usually show that the unit has been designed to give a fairly high concentration of light directly beneath it, but that also a great proportion is spread out in zones and at such angles that light is provided in areas at some distance from a point directly beneath the luminaire. Therefore, for general overhead lighting the units should be mounted as high as is expedient with their distribution so that every point in the room may be lighted from several directions (thus reducing the evil of sharp shadows), and that the room may be lighted as uniformly as possible. Wherever a high concentration of light is necessary, a local lighting unit should be used to supplement, not replace, the general overhead system.

Important Relation Between Foot-Candle and Lumen

Referring to Fig. 4B it may be seen that the surface *OPQR* is illuminated at every point to an intensity of 1 foot-candle. By definition the quantity of light falling on the plane *OPQR* is 1 lumen. This gives the important relation that if 1 lumen is so utilized that all of the light is spread over a surface of 1 square foot, that surface will be lighted to an average level of 1 foot-candle. This relation greatly simplifies the designing of a lighting installation, for once the number of square feet to be lighted and the foot-candle of illumination which it is desired to

provide are known, it is a simple matter to find how many lumens must fall on the working plane. If, for example, it is desired to illuminate a surface of 100 square feet to an average of 10 foot-candles, 1000 lumens must be projected on the surface. The designing of a lighting installation is taken up more in detail in *Bulletin 41—Illumination Design Data.*

Photometry

Candlepower and Light-Output Measurements

Photometry is a specialized branch of the science of illumination which in itself may be made the subject of extended study. The man doing field work in illumination has no need for an intimate knowledge of all the details that enter into this branch of the art. In the following pages photometers are discussed briefly; for more detailed description of these instruments the reader is referred to standard works on the subject of illumination and photometry.

A sketch of the most simple type of photometer is given in Fig. 8. The principal part of this photometer is a vertical paper screen between the lamps to be compared, at the center of which is a grease spot. When the illumination on one side of the screen is greater than that on the other, the spot will on this side appear darker and on the other side

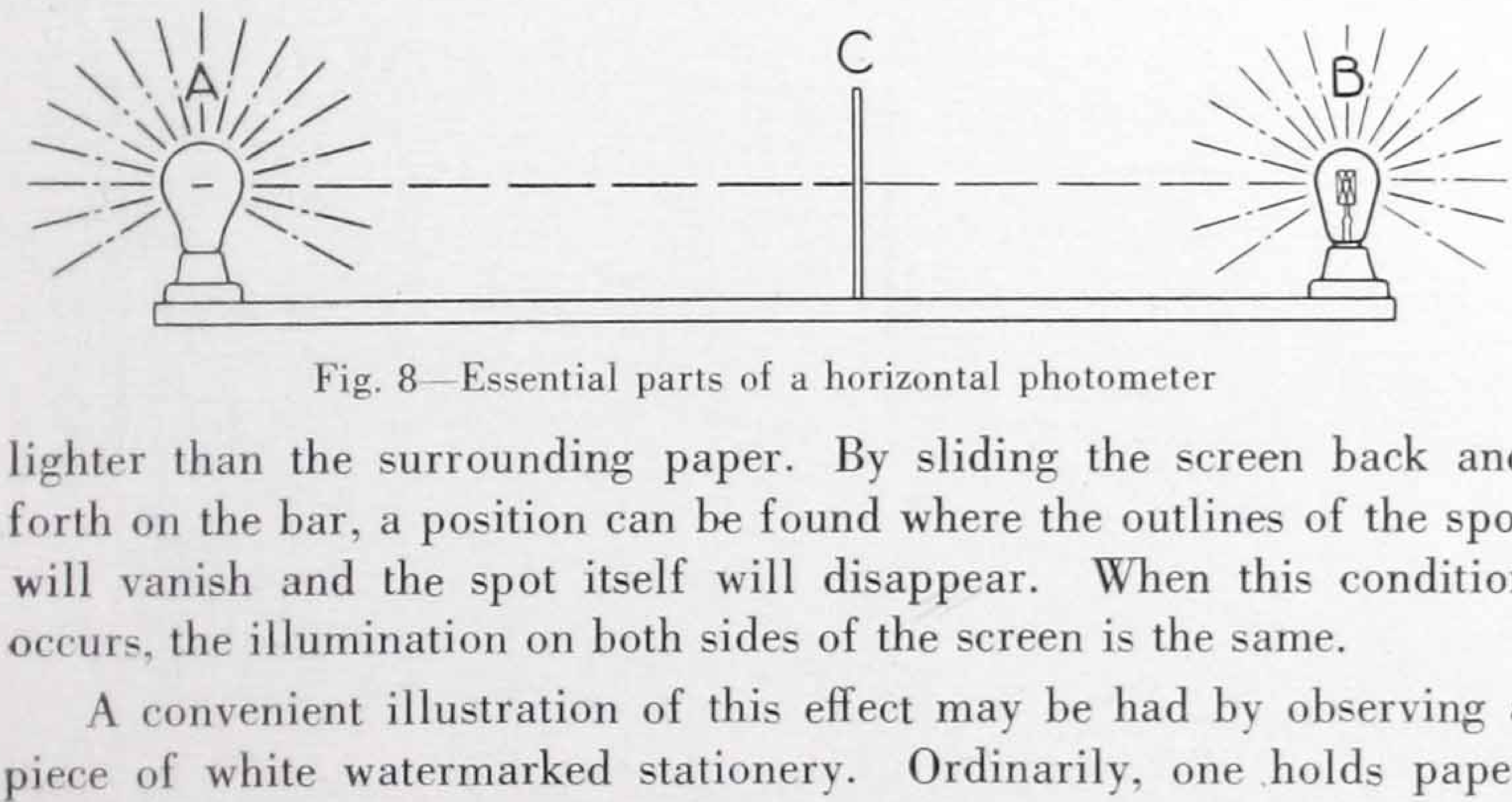


Fig. 8—Essential parts of a horizontal photometer

lighter than the surrounding paper. By sliding the screen back and forth on the bar, a position can be found where the outlines of the spot will vanish and the spot itself will disappear. When this condition occurs, the illumination on both sides of the screen is the same.

A convenient illustration of this effect may be had by observing a piece of white watermarked stationery. Ordinarily, one holds paper up to the light to see the watermark, which appears lighter because more light comes through the treated parts. By placing the sheet on a dark surface, the watermark appears dark and may be quite as easily observed. When the paper is held so that the watermark fades out, the illumination on both sides is approximately the same.

In order that both sides of a photometer screen may be seen simultaneously, mirrors are mounted obliquely behind the screen, to facilitate comparison. In Fig. 9A, it will be noted that the spot as viewed in the right-hand mirror is lighter than its surroundings, which indicates that the left-hand side of the screen is illuminated to a higher intensity than the right. In B of the same figure, it will be noted that the conditions are reversed; the illumination on the right side of the screen is greater than that on the left. Somewhere between these two positions is a position at which the spot will cease to be visible, as shown in C of Fig. 9.

From what has been said above, the illumination on both sides of the screen in C is the same. Since there is a relation between the amounts of illumination that the two lamps being compared produce, the relation between the candlepowers given, respectively, by lamps X and Y (Fig. 9), may be determined. The scale of the photometer shows (C) that at a distance of 60 inches, the lamp X produces an illumination equal to that which the lamp Y can produce at a distance of 40 inches.

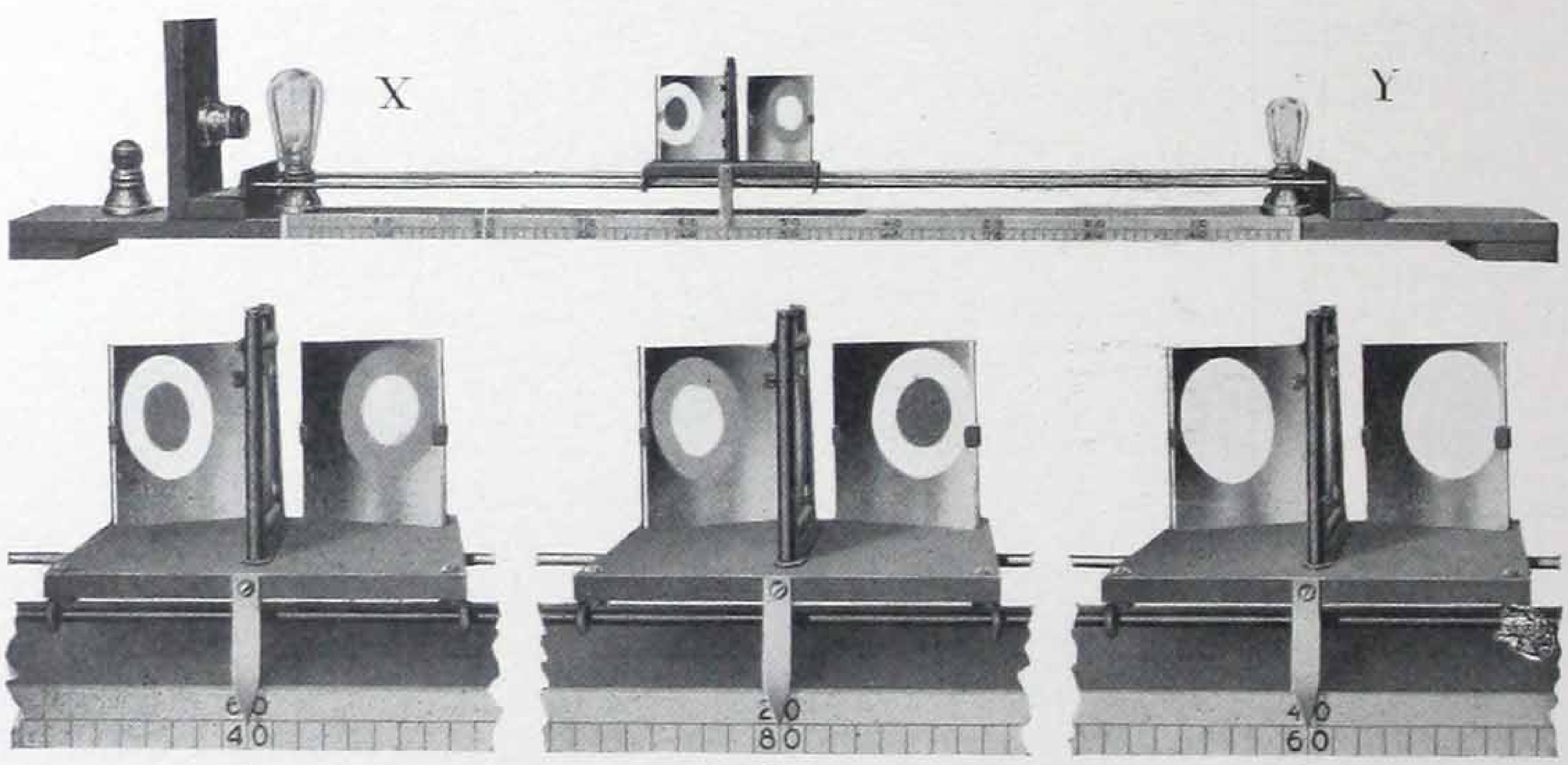


Fig. 9—Bunsen photometer and screens
A—Screen at left of balance point
B—Screen at right of balance point
C—Screen at balance point

At first thought it might seem that X must be 3/2 the candlepower of Y, but recalling the inverse square law (page 12), it is seen that the ratio of the candlepower of X to that of Y is 3^2 to 2^2, or 9 to 4. The horizontal candlepower of X, therefore, is $2\frac{1}{4}$ times that of Y. The general rule, then, is that the candlepower of two lamps on a photometer are to each other as the squares of the distances from each

to the screen. For accurate photometry, the grease spot screen is no longer in use, but modern photometers are the same in principle.

Customarily in the latter, a Lummer-Brodhun cube is used in which two prisms receive light from the sources to be compared, the beams being refracted by the prisms to parts of a pattern. In operation the position of the comparison lamp is adjusted until all parts of the pattern are uniformly bright.

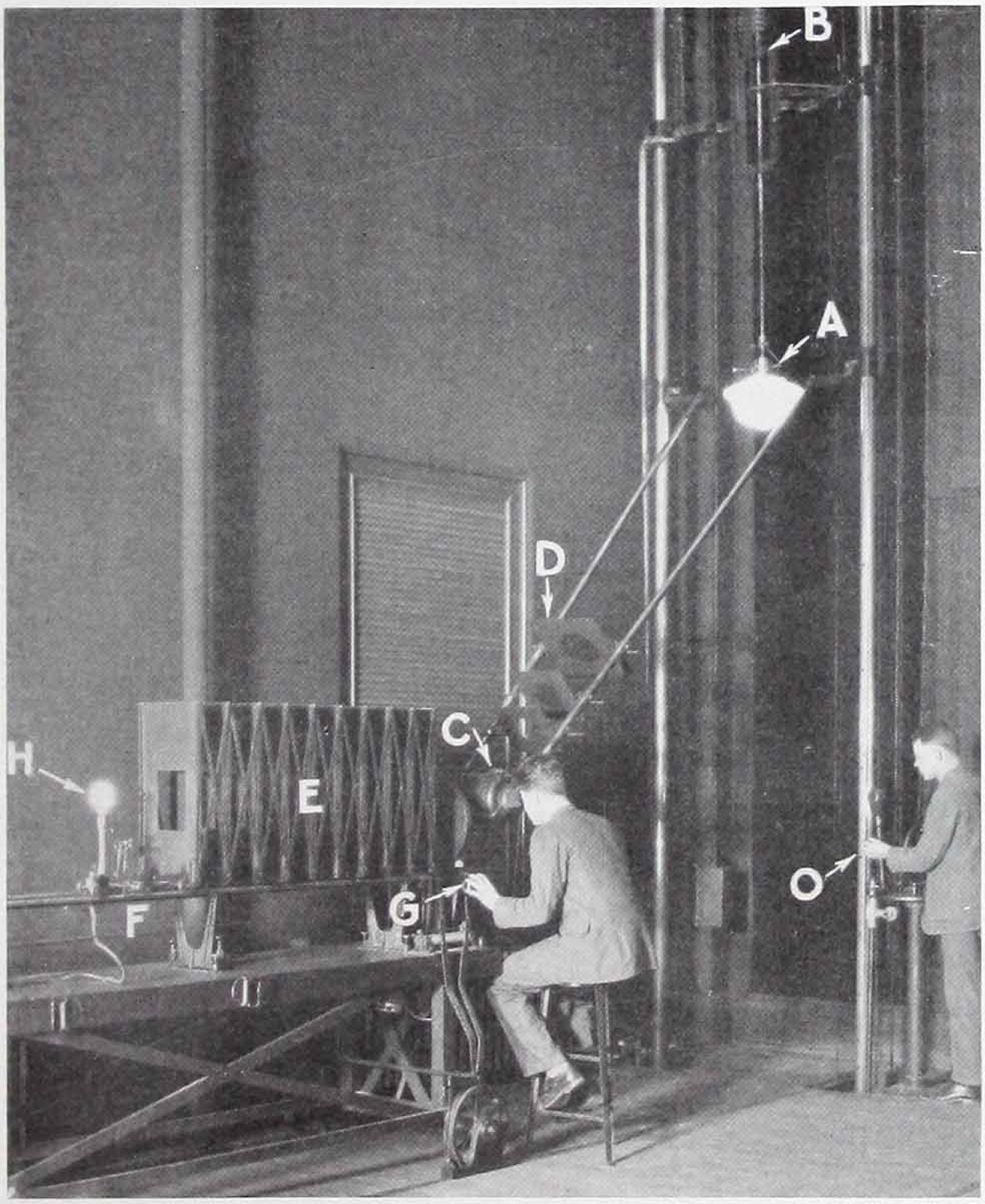


Fig. 10—Dibdin Photometer

The Dibdin photometer, Fig. 10, is used principally for obtaining candlepower curves of modern lighting equipment. The light from a comparison lamp *H* passes through the baffles *E*, the illumination on the comparison screen being varied by moving the standard lamp. The control is indicated at *G*. The lighting unit to be measured is mounted

at A, and is revolved by the mechanism at B. The contactors are shown just above the arrow. The operator on the right regulates at O the position of the lighting unit; the other operator balances at C the standard source against the light from the unit coming through the baffles at D. From the readings obtained at 10-degree intervals, the mean zonal candlepowers are obtained, and from these the total light output and the efficiency of the unit may be computed.

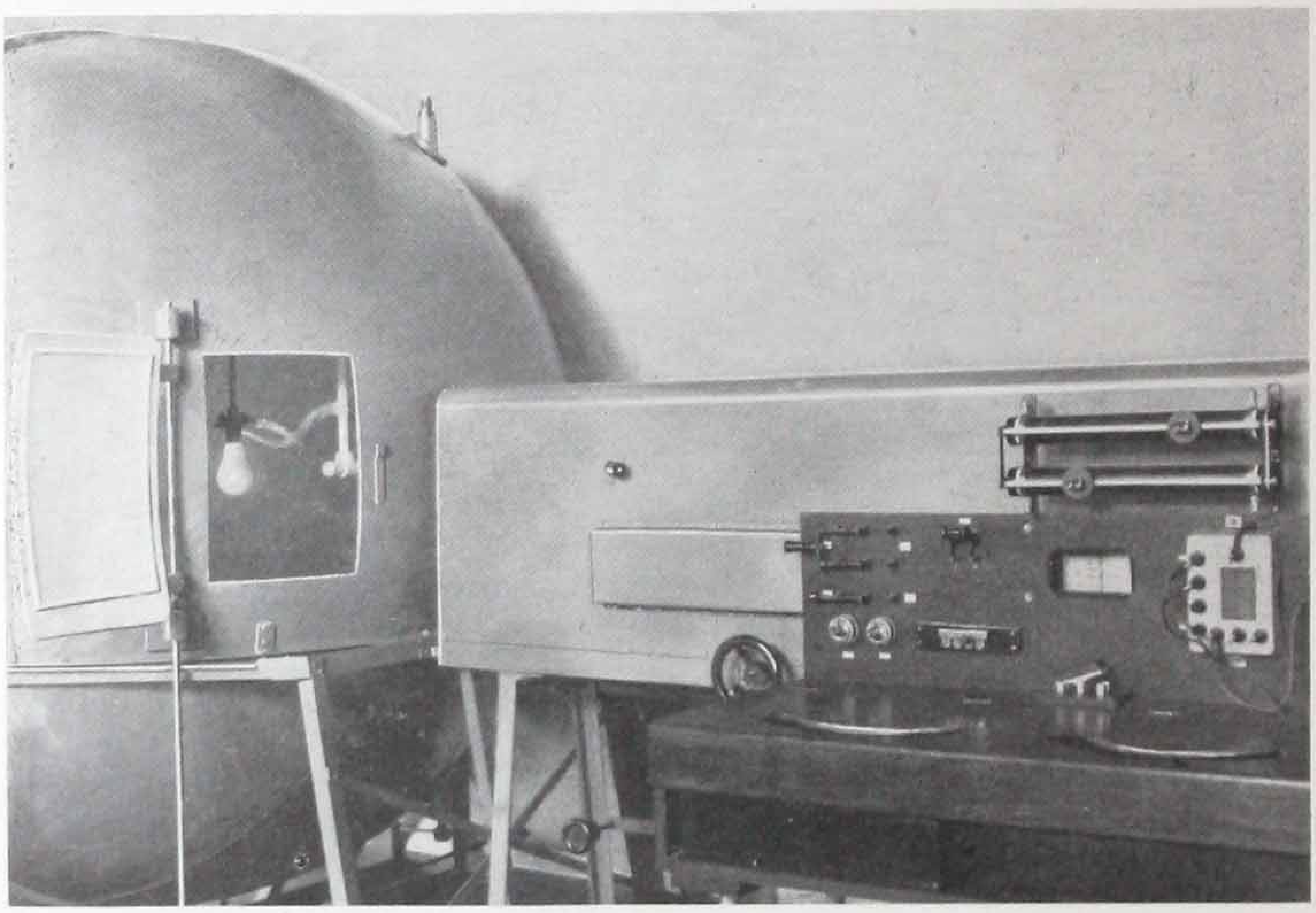


Fig. 11—Sphere photometer

Another form of photometer known as the sphere photometer, or Ulbricht Sphere, is shown in Fig. 11. In this photometer the lamp to be measured is placed at the center of the sphere (generally large in diameter), whose inner surface is painted flat white. In this sphere is a small window of milk glass, and this window is shielded from the direct rays of the lamp by a small opaque screen. The candlepower of the light emitted by the window is compared with the candlepower of a standard lamp. The candlepower of the light from the window is directly proportional to the mean spherical candlepower or the total lumen output of the lamp in the sphere,* so that multiplying this candlepower by a constant factor determined for this particular sphere

*That the above condition is true can be proved mathematically, but a discussion of this proof, important as it is in simplifying the operation of determining total light output, is beyond the scope of this bulletin.

gives the total lumen output directly. Thus at one reading the mean spherical candlepower or the total lumen output of a lamp can be determined.

The Candlepower Distribution Curve

The candlepower distribution curve of a lamp or unit was at one time widely used in calculating the illumination at certain distances from the source, but the lumen method of computing illumination was shown to be so much more accurate and simple that the former method has fallen into disuse. Distribution curves are now used principally for design information and for comparing reflectors for a given service from the standpoint of light distribution and light absorption.

Most photometers for mean spherical candlepower readings are so constructed that the test lamp is operated in a base-up position. If the reflector is placed over the lamp in this position and the whole series of candlepower measurements repeated, the combined effect of the reflector and lamp can then be readily noted. The tabulation in Fig. 12a shows the results of such a test on a 100-watt lamp equipped with an opaque reflector similar in shape to an inverted bowl. In this tabula-

ANGLE	CANDLE-POWER
0	142.0
5	148.0
15	161.0
25	178.0
35	183.0
45	181.0
55	165.0
65	108.0
75	44.1
85	5.1
90	

Fig. 12a

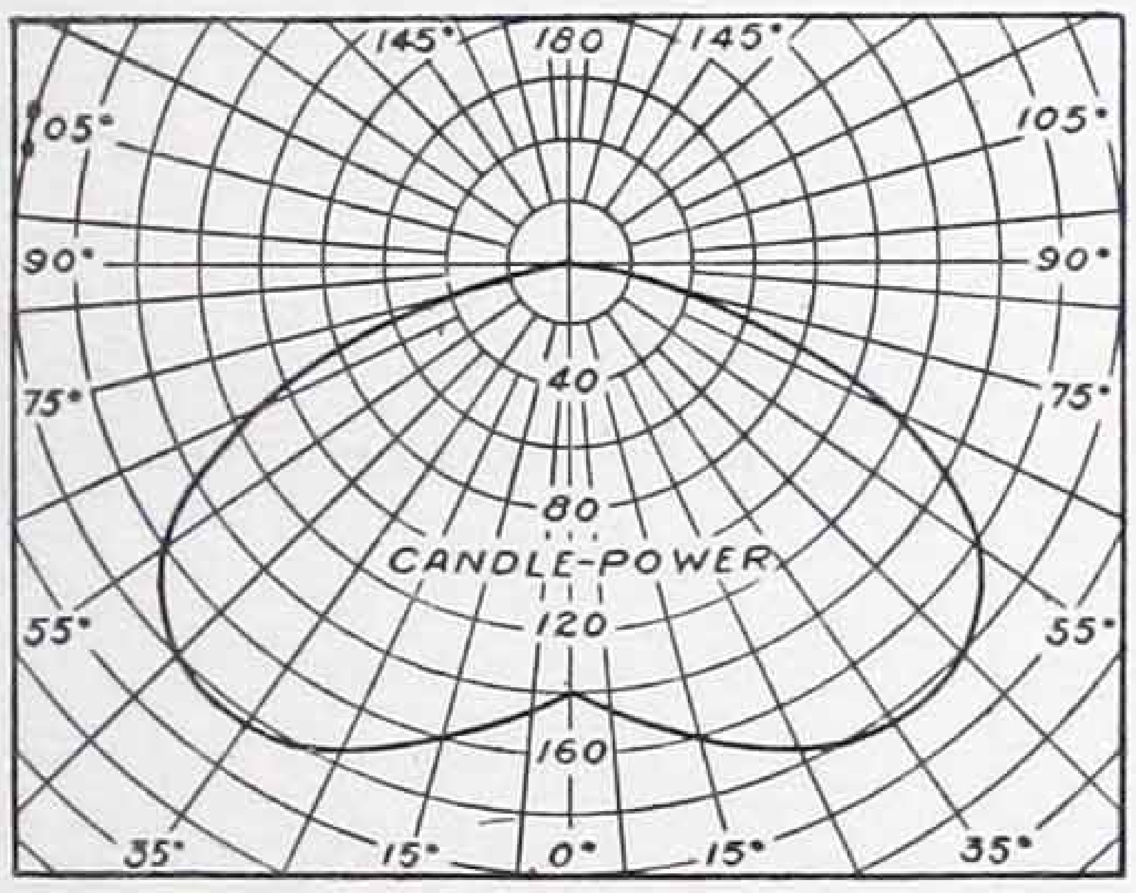


Fig. 12b

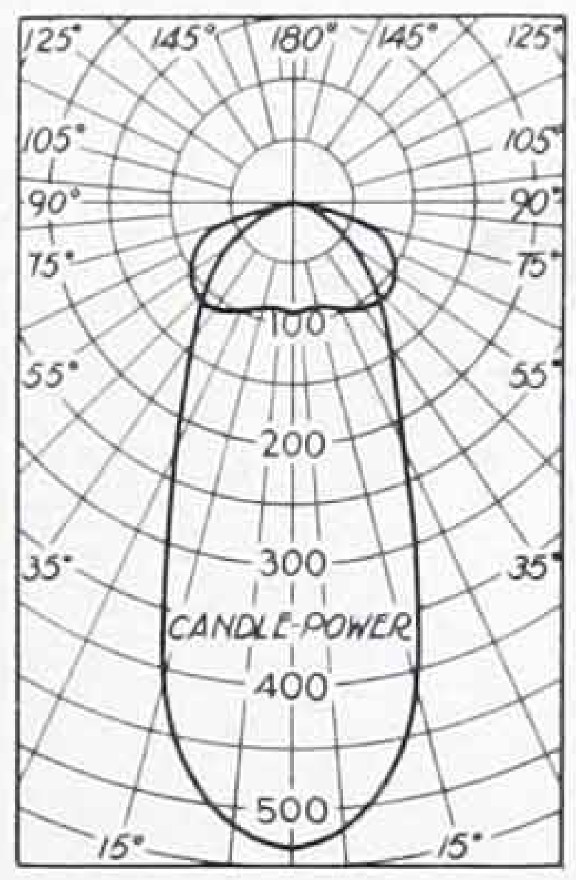


Fig. 13

Methods of recording candlepower measurements

tion 0° refers to the reading taken directly beneath the unit. The candlepower in this direction was found to be 142. Likewise 90° represents a measurement taken at the horizontal; due to the type of reflector chosen the candlepower at this and higher angles was zero. In Fig 12b a curve is shown. It will be noted that at each angle the curve passes through a point which corresponds to the tabulation in Fig. 12a, that is, the curve cuts the 0 line at 142, passes through 35° at 183 and cuts the 65° line at 108, etc. This diagram is commonly known as a distribution curve.

The area of a distribution curve is not a criterion of the total light output of a source. The two curves of Fig. 13 apply to two units which give exactly the same total lumens of light.

Another common error in the use of distribution curves is to assume that simply taking the arithmetical average of the candlepowers at different angles as shown on the distribution curve will give the mean spherical candlepower of the unit represented. To make the true relation more clear, assume that two men agree to paint the dome of a building in a series of 10° horizontal stripes and they decide to paint the same number of stripes each. If one started at the top, the other at the bottom, it may be readily seen by Fig. 14 that the amount of work per zone done by the man at 180° would be considerably less than that by the man at 90°. Similarly, a high candlepower in a zone near the vertical means much less lumens than in a zone near the horizontal.

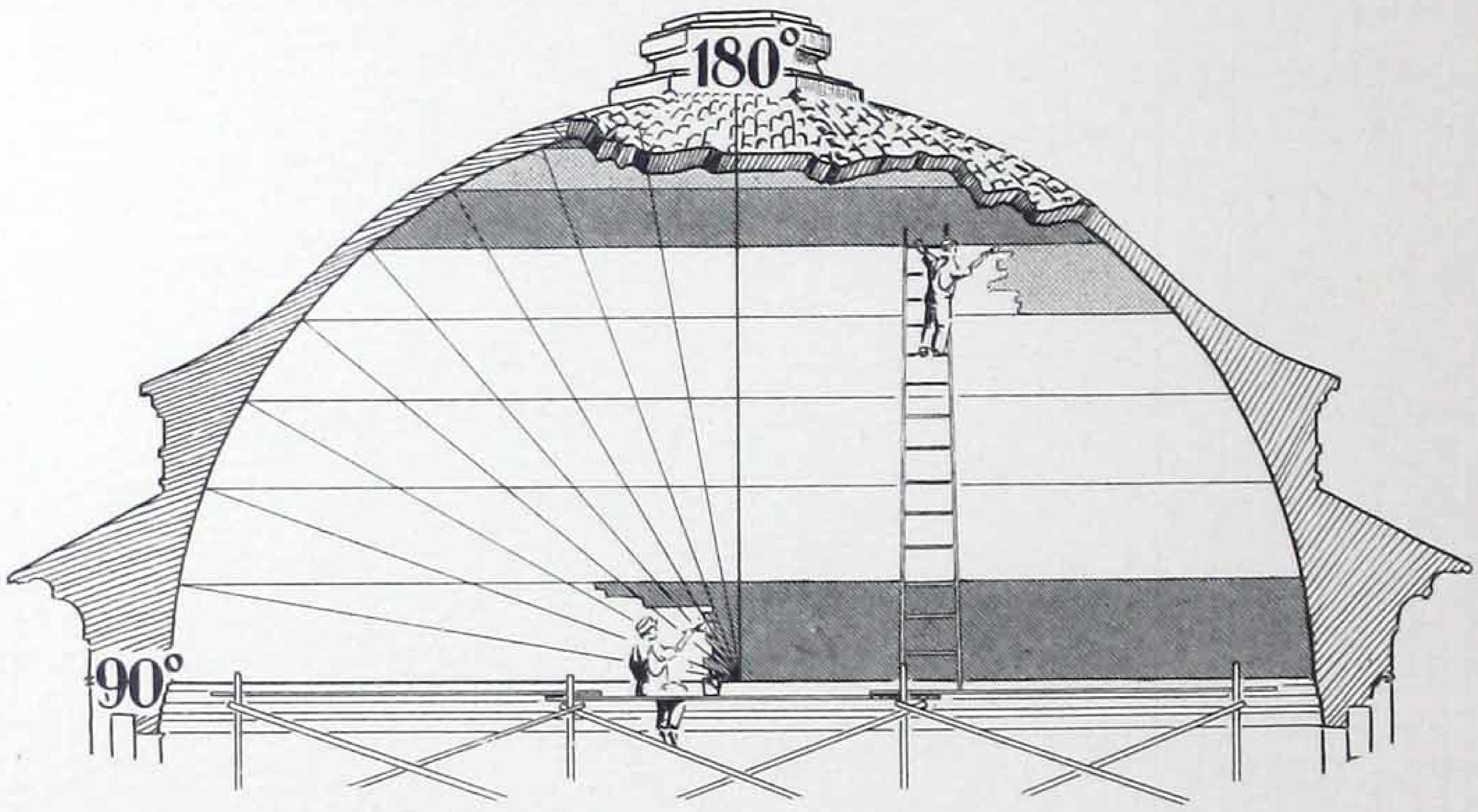


Fig. 14—Painting a 10° stripe at the 90° position is much more work than at the 180° position

In calculating the flux of light in various zones, it is usually found convenient to calculate for zones of 10 degrees, assuming that the candlepower at the center of the zone represents its average candlepower. The following are factors by which such candlepower values should be multiplied to give the lumens in each 10-degree zone:

Zone	Factor to obtain Lumens From Average C-P.	Zone	Factor
0°—10°	0.095	40°—50°	0.774
10°—20°	0.283	50°—60°	0.897
20°—30°	0.463	60°—70°	0.992
30°—40°	0.628	70°—80°	1.058
		80°—90°	1.091

Above 90 degrees the factors are the same but in the reverse order.

To use these factors with the curve of any lighting unit, the candlepower at 5 degrees is multiplied by the 0-10 degree factor to obtain lumens in the 0-10 degree zone; the candlepower at 15 degrees is multiplied by the 10-20 degree zone factor to obtain the lumens in the 10-20 degree zone, etc. The total lumens for any large zone is the sum of the lumens thus determined in all of the 10-degree sections of the zone.

Another method of determining the flux in any 10-degree zone is as follows: First measure the horizontal distance between the vertical axis and the point where the candlepower curve crosses the center of the zone under consideration. Then lay off this distance on the candlepower scale to which the curve is plotted. By adding 10 per cent to this figure, a value which represents the lumens in that zone, is obtained. If it is desired to obtain the summation of the lumens in a number of 10-degree zones, for example from 0 degrees to 60 degrees, it is convenient to mark off these horizontal distances (to the center of each 10-degree zone) successively on the edge of a sheet of paper. The value for the total lumens is then found by simply laying off the total length thus found on the candlepower scale and adding 10 per cent to the result. The results obtained by this method, neglecting possible errors of measurement, are accurate within .2 of one per cent.

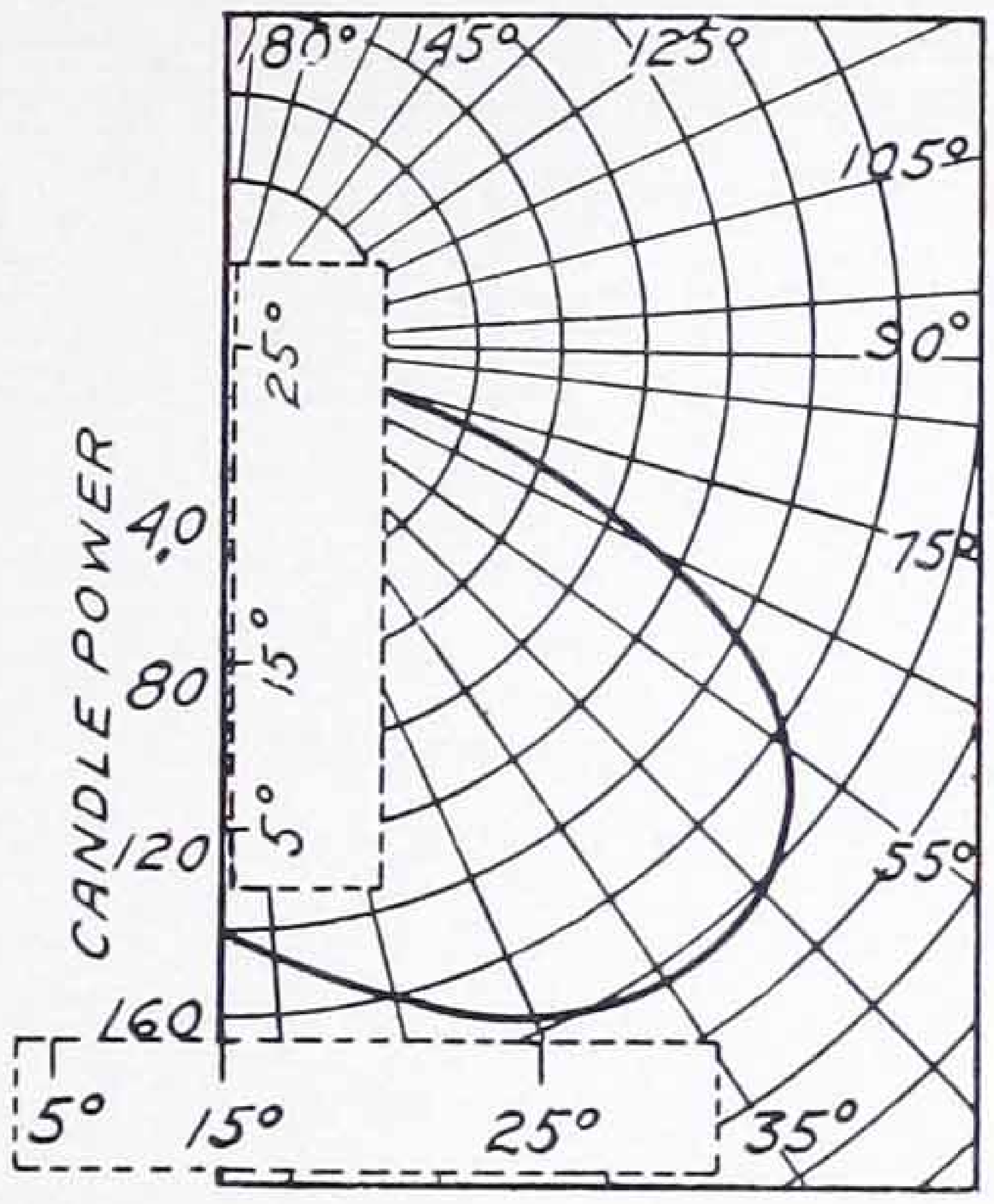


Fig. 15—On the strip the horizontal distance to the 5° point on the curve is measured off, the horizontal distance to the 15° point is added; the lower strip is shown in the position of adding the distance to the 25° point. Adding 10% to the total length and measuring it on the candlepower scale gives the total lumens in the zones measured.

Foot-Candle Measurements

It will be noted that in measuring the candlepower of light sources as discussed above, the *illumination* on opposite sides of a screen is balanced. Often, however, we are interested in the illumination itself, that is, the foot-candle level which is being supplied any given area, and care very little about the candlepower of the sources which supply the illumination. If we calculate the different foot-candle intensities to which one side of the screen of a photometer is illuminated when the distance between the screen and the standard lamp is varied, and then

place the screen so that the illumination to be measured falls upon the opposite side of the screen, the balance of the photometer will give us a measurement of the illumination in foot-candles. The differences between photometers used for measuring candlepower and those used for measuring foot-candles are chiefly ones of form and calibration.

Fig. 16—Foot-candle meter

Types of Illumination Meters

A number of good portable and semi-portable instruments are now available for use in measuring footcandlage. The one in most common use is the foot-candle meter. It is very simple to operate, it is so light that it can easily be carried about, and it is so small that it can be used in very restricted places. In operation, the foot-candle meter is placed upon or adjacent to the surface on which a measurement of the foot-candle level is desired, the voltmeter needle is brought to position, and the reading may be taken. Referring to Fig. 16, a small incandescent lamp concealed within the box at the right hand end of the screen, illuminates the translucent spots on the screen to a high intensity at one end and low at the other. The illumination to be measured is assumed to be practically uniform over the entire scale. If the illumination to be measured falls within the limits of the meter (.1 to 100 foot-candles), the spots will appear bright at one end of the scale and dark at the other. At the point where the spots are neither brighter nor darker than the paper scale, where the spot seems to fade into the scale, the illumination from without and within are equal, and the foot-candles of illumination can be read directly. The scale is calibrated with the lamp within the box burning at a certain definite voltage; a voltmeter and rheostat enables the operator to obtain this voltage for each reading. "One-tenth" and "double scale" are provided. Energy is supplied by a small flashlight battery.

This instrument is proving very serviceable for "checking-up" an installation to insure, for example, that the illumination is correct when the lighting equipment is first installed and to see that it is not allowed to fall below a reasonable value because of improper care and attention to maintenance.

The Weber photometer, an imported instrument, consists of two tubes at right angles, at the junction of which is a Lummer-Brodhun cube, so arranged that the illumination from the source and standard lamp are observed simultaneously, and balanced by the operator. Tube *A* contains, at the far end, a diffusing glass plate where the light to be measured enters, and at the other, the eye-piece. The comparison standard at the end of the tube *B*, was formerly a benzine flame but is generally replaced by a miniature lamp and storage battery, as

Fig. 17—Types of portable photometers (showing approximately comparative size)

shown. The comparison lamp illuminates a milk-glass plate which is moved back and forth in the tube B, and carries with it a pointer moving along the scale.

In the Sharp-Millar photometer the comparison lamp is mounted on a carriage which travels along a track. The carriage is moved by a cord drive manipulated by the knob at the center of the

instrument. The scale of the instrument is translucent and is lighted by the comparison lamp; the shadow of a fine crosswire indicates the reading. At the left end of the box is the optical device, a Lummer-Brodhun prism set. The elbow tube, containing a milk-glass test plate, may be rotated to facilitate taking measurements in any direction. Standard equipment of the photometer includes test plates for the measurement of illumination intensities and for the determination of candlepower, and filters for increasing the range of the instrument.

The Macbeth Illuminometer is a more compact instrument of the same general character. A rod mounted on a rack-and-pinion gear slides in a metal case. The rod has the comparison lamp at one end and the electrical connections to the milliammeter and battery in the case at the other. The scale is on the front face of the rod. The eye-piece, elbow tube fitted with a mirror, and prism cube are in line at the left end of the instrument. The test plate, as shown, is mounted on a tripod.

Part II—Principles of Light Control

THE light from a bare incandescent lamp is distributed in a manner such that under most conditions it cannot be employed effectively without the use of reflectors or enclosing glassware. Such accessories should not only redirect light which would otherwise be ineffective into useful angles, but should serve to modify the brilliancy of the light source, diffusing the light to produce a soft and pleasing illumination.

Three systems of lighting are commonly employed. They have been referred to as *direct, indirect,* and *semi-indirect.* In the direct-lighting system, the units distribute the light downward into the room; in the indirect system, all of the light is thrown upon the ceiling and thence reflected into the room; in the semi-indirect system, a greater part of the light is thrown upon the ceiling and a smaller part passes through the luminaire and directly into the room.

In screening and redirecting light, three classes of substances are used: *transparent, translucent,* and *opaque. Transparent* substances transmit a large fraction of the light striking them without scattering it, hence objects may be seen clearly through transparent plates. *Translucent* substances transmit light, but scatter it so that the outlines of objects cannot be clearly seen through them. *Opaque* substances transmit none of the light, but it is either reflected or absorbed. Substances differ widely in these properties, varying from almost perfect transparency to complete opacity. All substances, whether transparent, translucent, or opaque, absorb a certain proportion of the light rays incident upon them, and the radiant energy so absorbed tends to raise the temperature of the substance.

Opaque bodies depend entirely upon reflection for their control of light. Reflected light is that thrown back or redirected by a surface, much as a tennis ball is stopped and redirected when it comes in contact with a racket.

A ray of light will travel along a straight line indefinitely until it is modified or redirected by some agency. Such modification may be in the nature of *absorption* by the medium through which it passes or by the object upon which it impinges. This is noticed when a beam of light passes through a smoky atmosphere, through a piece of smoked glass, or meets a black opaque body. In these cases, a part or practically all of the light loses its identity as such and is converted into

TABLE II—CHARACTERISTICS OF MATERIALS

Material	Light Reflected			Light Transmitted			Light Absorbed
	In Concentrated Beam	In Spread Beam	Diffused in All Directions	In Concentrated Beam	In Spread Beam	Diffused in All Directions	
Crystal Glass—							
Clear	8–10*	....	....	80–85	....	....	5–10
Frosted or Pebbled (A)	4–5	5–10	....	....	70–85	....	5–15
Frosted or Pebbled (B)	....	8–12	....	....	72–87	....	5–15
White Glass—							
Very Light Density (A)	4–5*	....	10–20	5–20	....	50–55	8–12
Very Light Density (B)	....	3–4	10–20	....	5–20	50–55	10–15
Heavy Density	4–5*	....	40–70	....	....	10–45	10–20
Mirrored Glass	82–88	....	....	....	....	....	12–18
Polished Metal—							
Silver	92	....	....	....	....	....	8
Chromium	65	....	....	....	....	....	35
Aluminum	62	....	....	....	....	....	38
Nickel	55	....	....	....	....	....	45
Tin	63	....	....	....	....	....	37
Steel	60	....	....	....	....	....	40
Porcelain Enamel Steel	4–5*	....	60–70	....	....	....	25–35
Mat-Finished Metal—							
Aluminum	....	62	....	....	....	....	38
White Oxidized Aluminum	....	70–75	....	....	....	....	25–30
Aluminum Paint	....	60–65	....	....	....	....	35–40
Mat Surfaces—							
White Plaster	....	....	90–95	....	....	....	5–10
White Blotting Paper	....	....	80–85	....	....	....	15–20
White Paper (Calendered)	4–5*	....	75–80	....	....	....	15–20
†White Paint (Dull)	....	....	75–80	....	....	....	20–25
White Paint (Semi-mat)	....	2–4	70–75	....	....	....	20–25
White Paint (Gloss)	4–5*	....	70–75	....	....	....	20–25
Black Paint (Gloss)	4–5*	....	3–5	....	....	....	85–92
Black Paint (Dull)	....	....	3–5	....	....	....	95–97
Magnesium Carbonate	....	....	98–99	....	....	....	1–2

(A) Smooth side toward light source.
(B) Roughed on side toward light source.
* For angles up to 45°; for angles greater than 45° this value rises considerably, as shown in Fig. 25; angle of incidence as X, Fig. 18.
† For colored paints see page 11, and color plates in Bulletin 41—Illumination Design Data.

heat. A second form of modification is termed *refraction.* Refraction is a bending of the ray of light due to its passing from one transparent medium to another of greater or less density, as, for example, from air to water or from air to glass. A very common instance of refraction is the apparent bending of a fish line at the point where it enters the water; as a matter of fact, the line is straight but the light rays coming from that part of the line which is under the water are refracted when they pass from water into air. A third form of modification of a ray of light is *reflection,* which is the throwing back or redirection of the ray by a surface. A fourth form is *diffusion,* which is the breaking up of the beam and spreading of its rays in all directions by the medium through which it passes or by the surface upon which it falls. By controlling these four methods—absorption, refraction, reflection, and diffusion, it is possible to make the light from any source perform practically as desired.

Polished-Metal and Mirrored-Glass Reflecting Surfaces

The simplest form of reflection is that which takes place when a ray of light strikes a polished-metal surface. As indicated in Fig. 18, a ray of light having a direction *sa* on striking a polished-metal surface

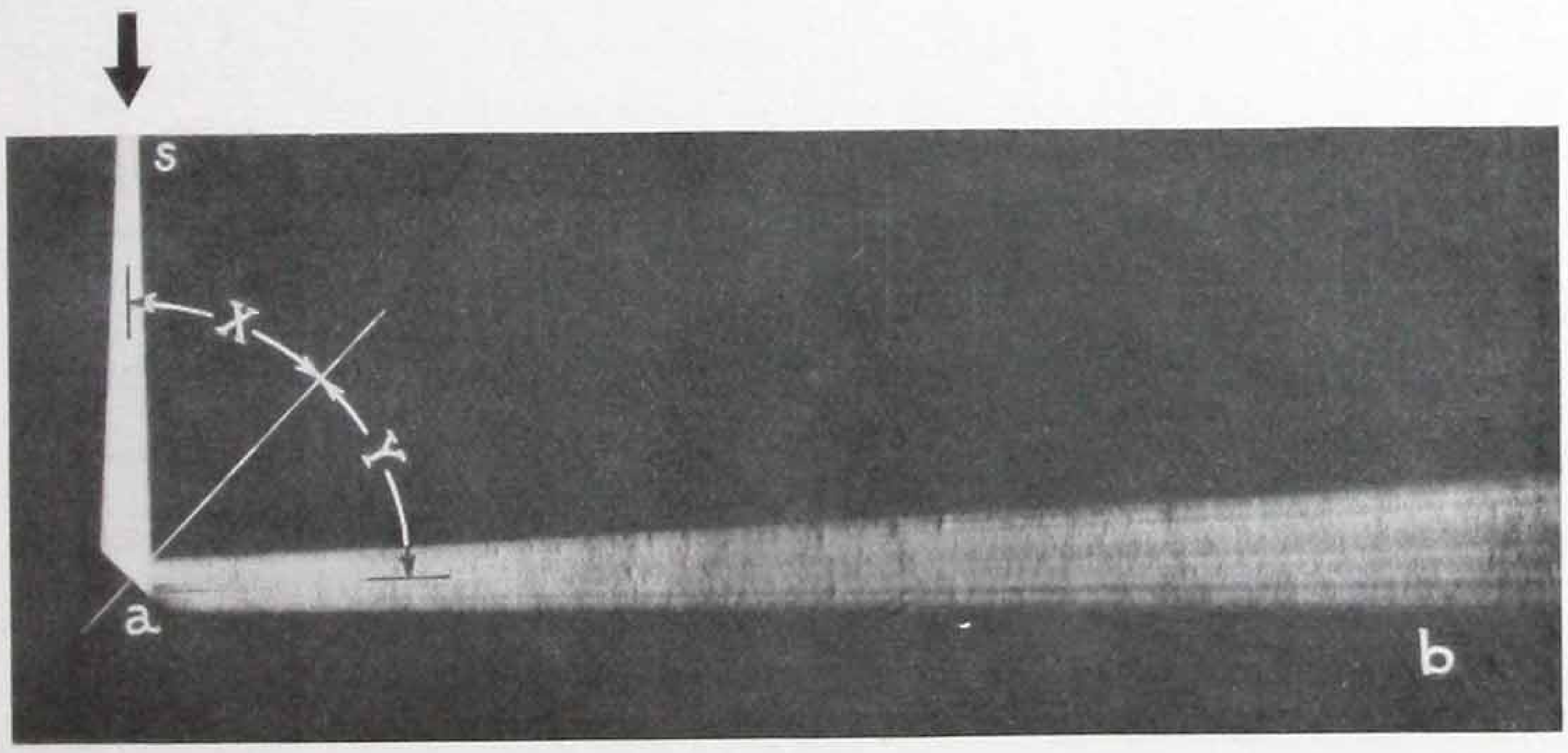


Fig. 18—Reflection from polished metal

is reflected off in the direction *ab,* so that the angle Y (called the angle of reflection) is equal to the angle X (called the angle of incidence) and practically no light is reflected in other directions. This is called

regular reflection. It will be seen, therefore, that it is possible to redirect light traveling in a given direction into any other desired direction by means of such a surface properly placed. When we consider that the schoolboy by means of a pocket mirror or piece of polished metal can take the beam of sunlight that comes in at the window and redirect it with remarkable accuracy to any place in the room, the general principle involved is seen to be simple. While all polished-metal surfaces reflect light in the manner described, they do not reflect it in like amounts. For instance, if two beams of 100 lumens each fall respectively on a polished-silver surface and on a polished-aluminum surface, the silver will reflect a little less than 90 lumens and the aluminum about 60 lumens. In other words, the silver surface will absorb only 10 to 12 per cent of the light while the aluminum surface will absorb about 35 to 40 per cent. All of the light falling on an opaque surface is reflected or absorbed by that surface.

Polished metal reflectors are used most extensively in equipment where they can be tightly covered to keep out dust, dirt, and tarnishing agencies, such as in automotive lighting equipment—as in headlights, spotlights, stoplights, etc.

Chromium plated reflectors have a number of characteristics which make them desirable for commercial use. They may be finished dull or bright; they have a high, well-maintained reflection factor of about 65 per cent, and they are not subject to tarnishing.

Similar to the reflection characteristics of polished metal are those of mirrored glass. Fig. 19 shows the path of a ray of light striking the surface of a commercial type of mirror with silvering on the back of the glass. A small part of the light is at once reflected by the polished surface of the glass without passing through to the silvered backing; the remainder passes through the glass to the silver, from which it is reflected through the glass again and out along a line parallel to the ray reflected from the glass surface. The fact that most of the light has to pass through the glass both to and from the reflecting surface makes the silvered mirror, from a laboratory standpoint, a less efficient reflecting surface than the polished silver itself. For instance, if 100 lumens strike a mirror the reflections and absorptions are of the following order of magnitude: 10 are reflected by the exposed surface of the glass, 10 are lost by being absorbed by the silvered surface, 5 are absorbed by the glass, and about 75 lumens are reflected by the

silvered surface, making a total output of 85 lumens. The loss in the glass depends, of course, on the quality of the glass. The deterioration of a polished-metal reflecting surface in service is, however, a factor which often more than offsets its higher initial efficiency.

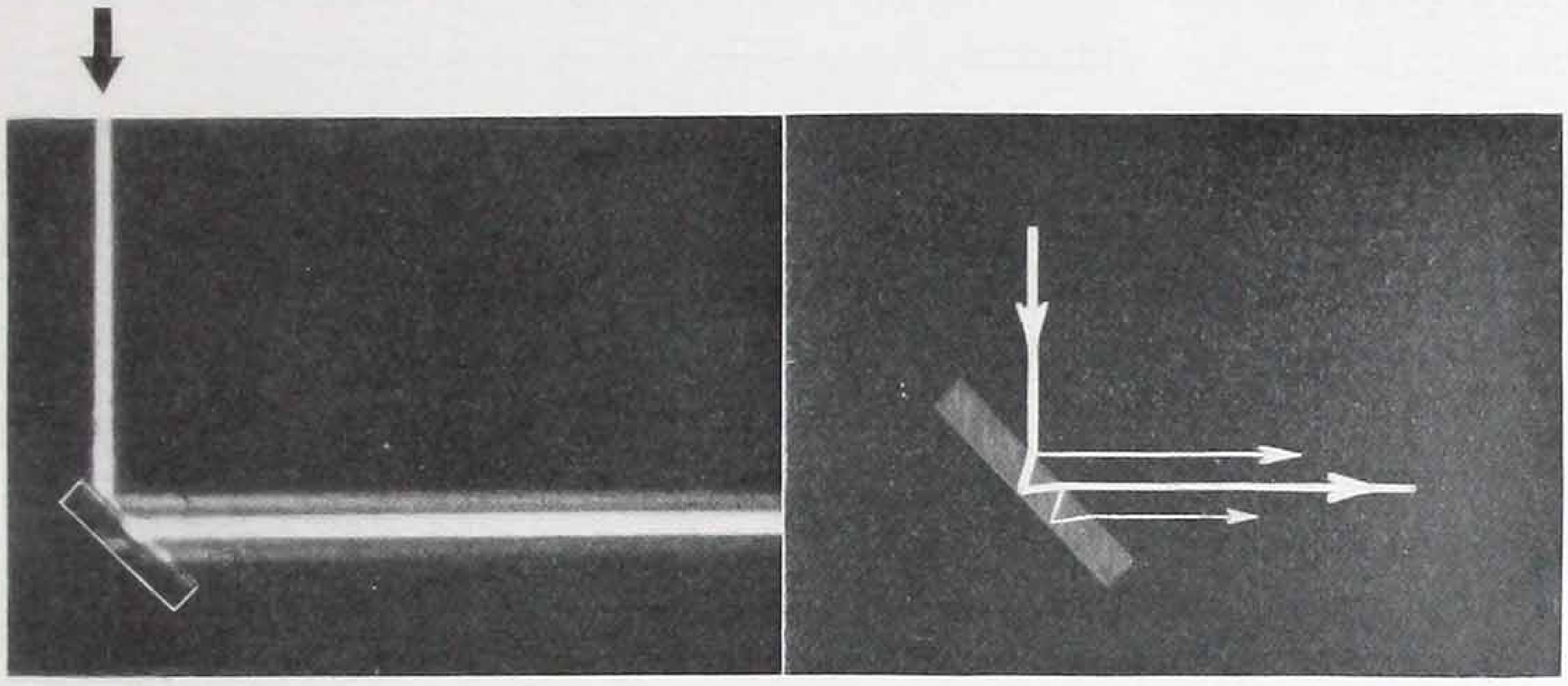


Fig. 19—Reflection from mirror. The upper third of the beam is directly reflected from the surface of the glass, the middle portion from the mirror surface, the lower third reflected as shown in the diagram.

To obtain a desired distribution from a polished-metal or a mirrored surface, it is necessary that the contour of the reflector at each point be such that it makes equal angles with the incident ray at that point and the desired direction of light. For example, where parallel rays of light are desired, as in the case of automobile headlights, the cross-section of the reflector will have to be curved so that the elements or infinitesimal planes of the curve each reflect light as a plane surface, in the desired direction. The resulting curve is the parabola (Fig. 21).

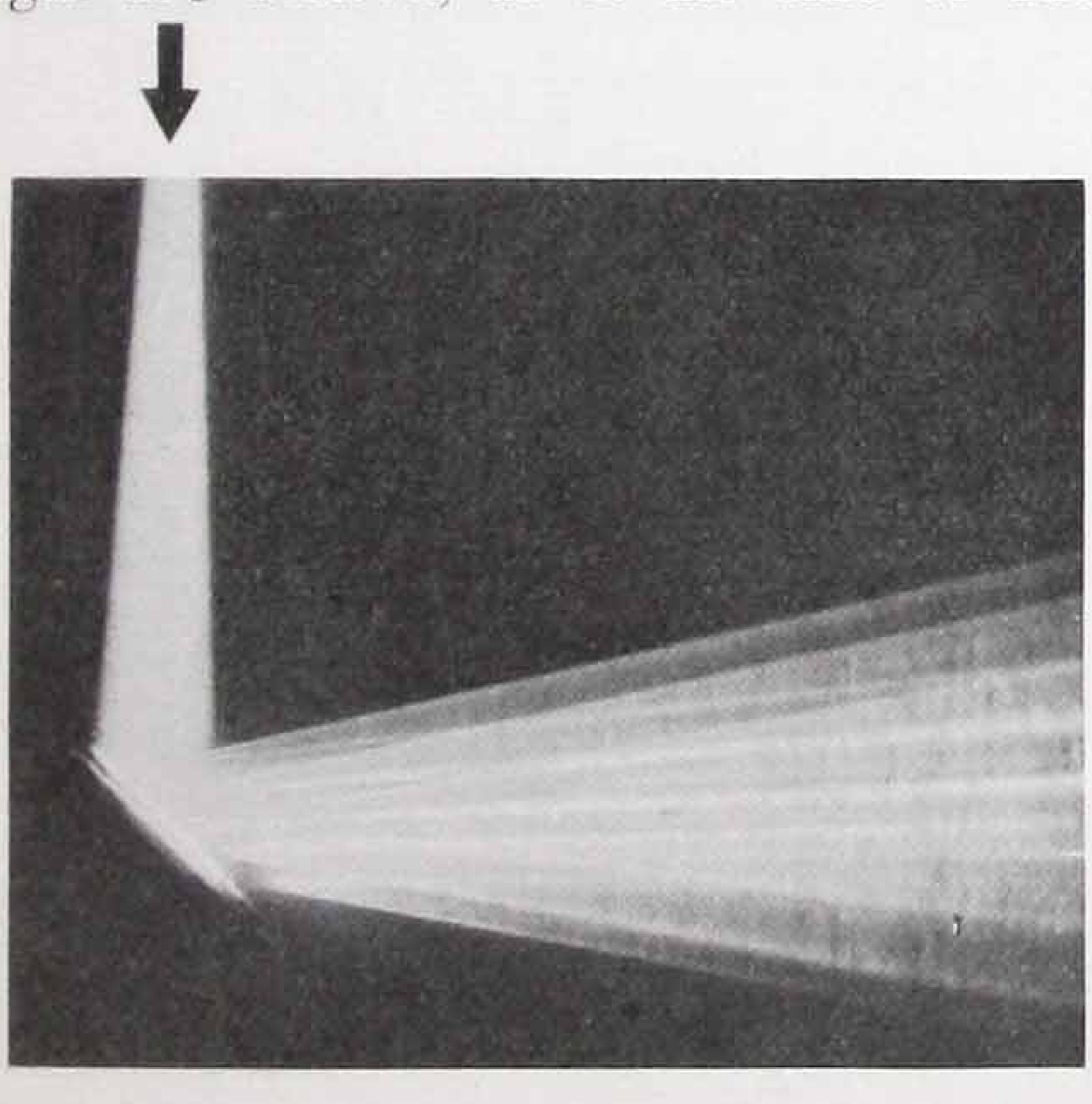


Fig. 20—Reflection from fluted mirror—the flutes divide the beam into segments.

On the other hand, a reflector of hemispherical shape placed above the lamp with its center coinciding with the light source, will not concentrate the light at all but will nearly double the candlepower at each angle in the lower hemisphere, since each ray that strikes the reflector

is reflected back along the same line, through the source and into the lower hemisphere.

Mirrored reflectors have the disadvantage that they usually throw brilliant images of the filament, or striations, on the surfaces illuminated. In practice, these striations are often eliminated by fluting the reflector or frosting the lamp, with, however, some loss in the control of the light.

In floodlights, show window reflectors, and motion picture projection machines, and in lighting equipment of the totally indirect type, much use is made of mirrored glass for the reflecting surface.

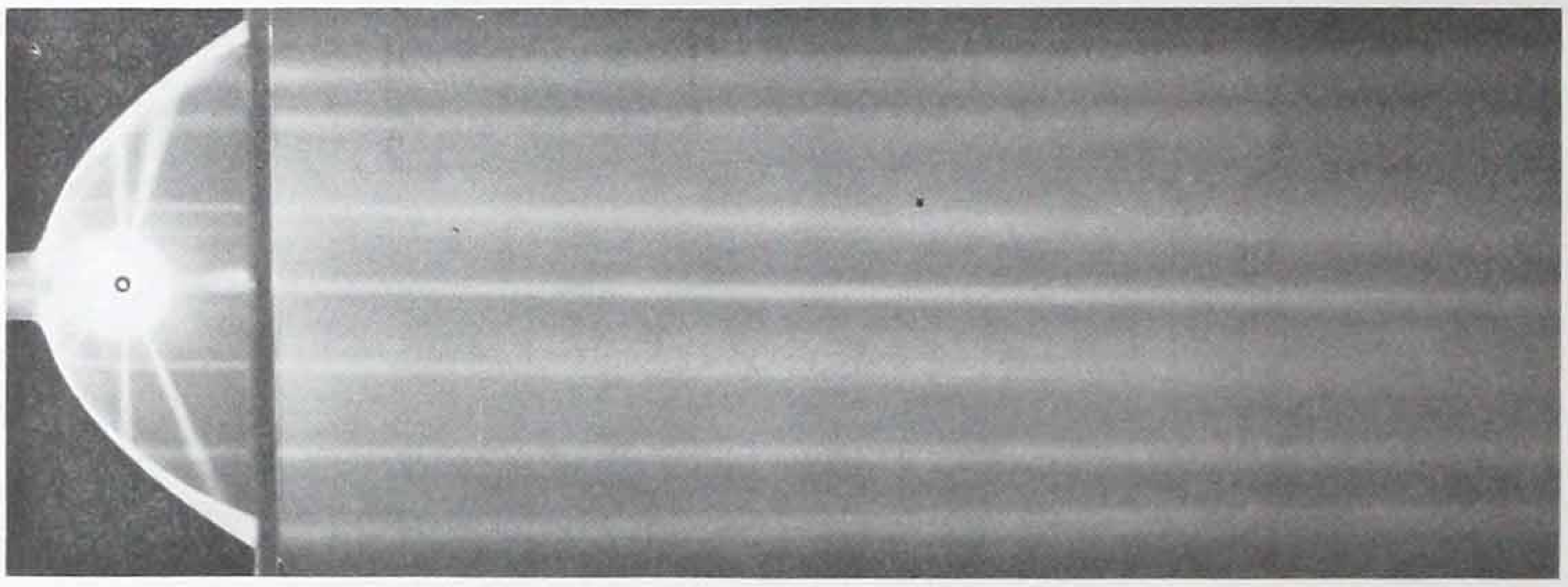


Fig. 21—Accurate light control may be obtained from polished-metal or mirrored surfaces—parabolic reflector

Dull-Finished Metal Reflecting Surfaces

An unpolished metallic reflector can be considered as one which has many small polished surfaces making innumerable slight angles with the contour. A velvet finish nickel surface or one coated with aluminum paint affords a good example. When a shaft of light strikes such a surface, the individual rays are reflected at slightly different angles, but all in the same general direction. This is known as spread reflection. The spread of the reflected beam is dependent upon the degree of smoothness of the surface, the smoother the surface, the narrower the angle. When the reflecting surface is viewed along the line *ba*, Fig. 22, no distinct image of the light source but only a bright spot of light is visible. Dull-finish reflectors redirect the light with less concentration than polished reflectors, but at the same time, streaks

and striations are largely eliminated. The greatest objection to the use of this type of surface for luminaires lies in the fact that they collect dust and dirt quickly and are therefore difficult to keep clean.

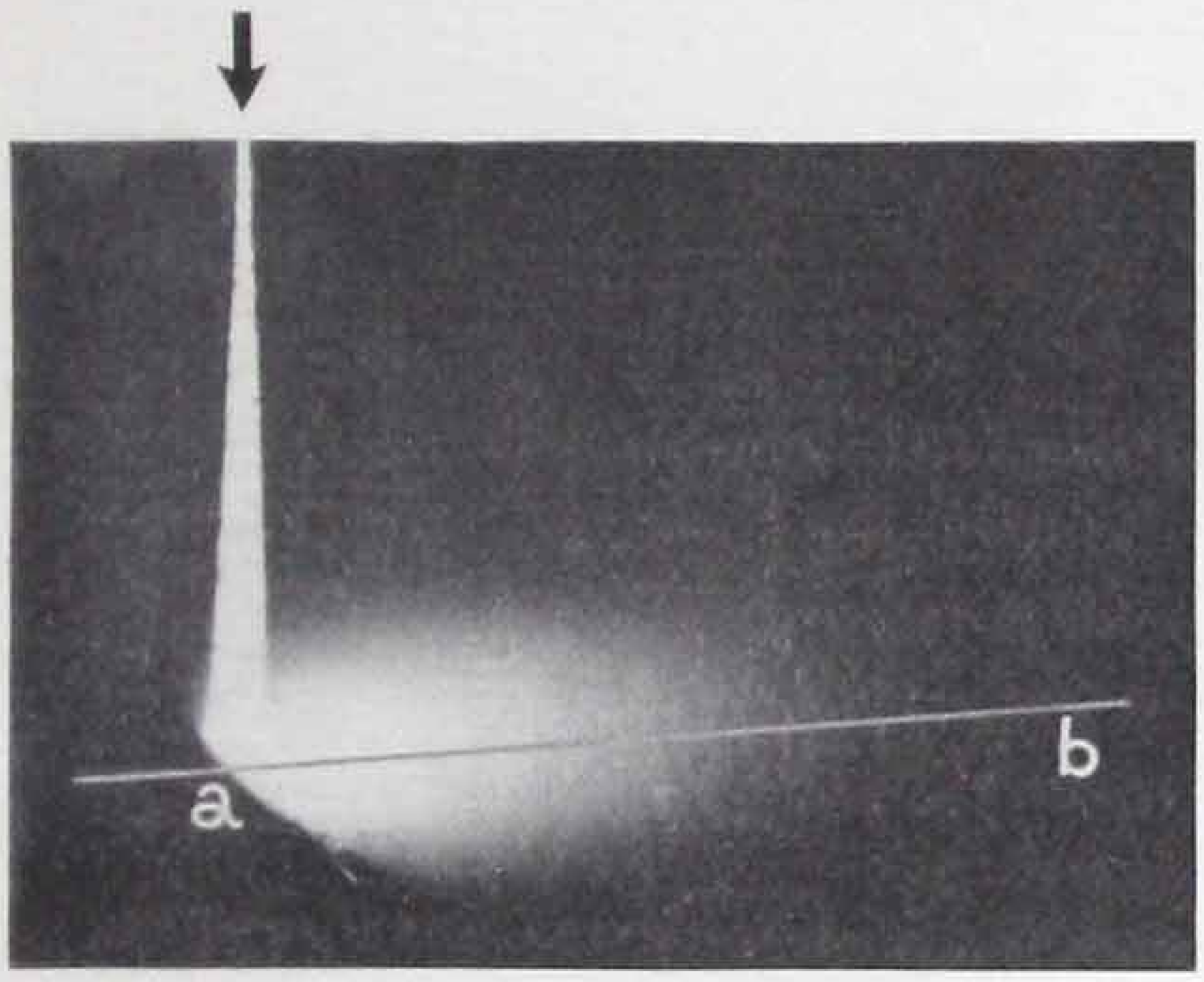


Fig. 22—Reflection from dull-finish surface—aluminum paint

The more common materials for this type of reflector are spun aluminum and aluminum-finish metal.

Light weight and low cost are characteristic of aluminum-finish and spun aluminum reflectors as used for spotlights, floodlights, desk lamps, etc.

Rough or Mat-Finish Reflecting Surfaces

If a surface is so rough that it has absolutely no sheen, a beam of light striking it will be reflected in all directions. A two-inch square of asbestos, for example, when placed in the path of a beam of light, will be equally bright, viewed from any angle. Even when the angle is such that the surface is apparently only one inch wide, the surface looks just as bright as though it were at right angles to the line of vision with twice as much area visible. It has the same relative brightness in all directions as though it were heated to incandescence. This is called diffuse reflection.

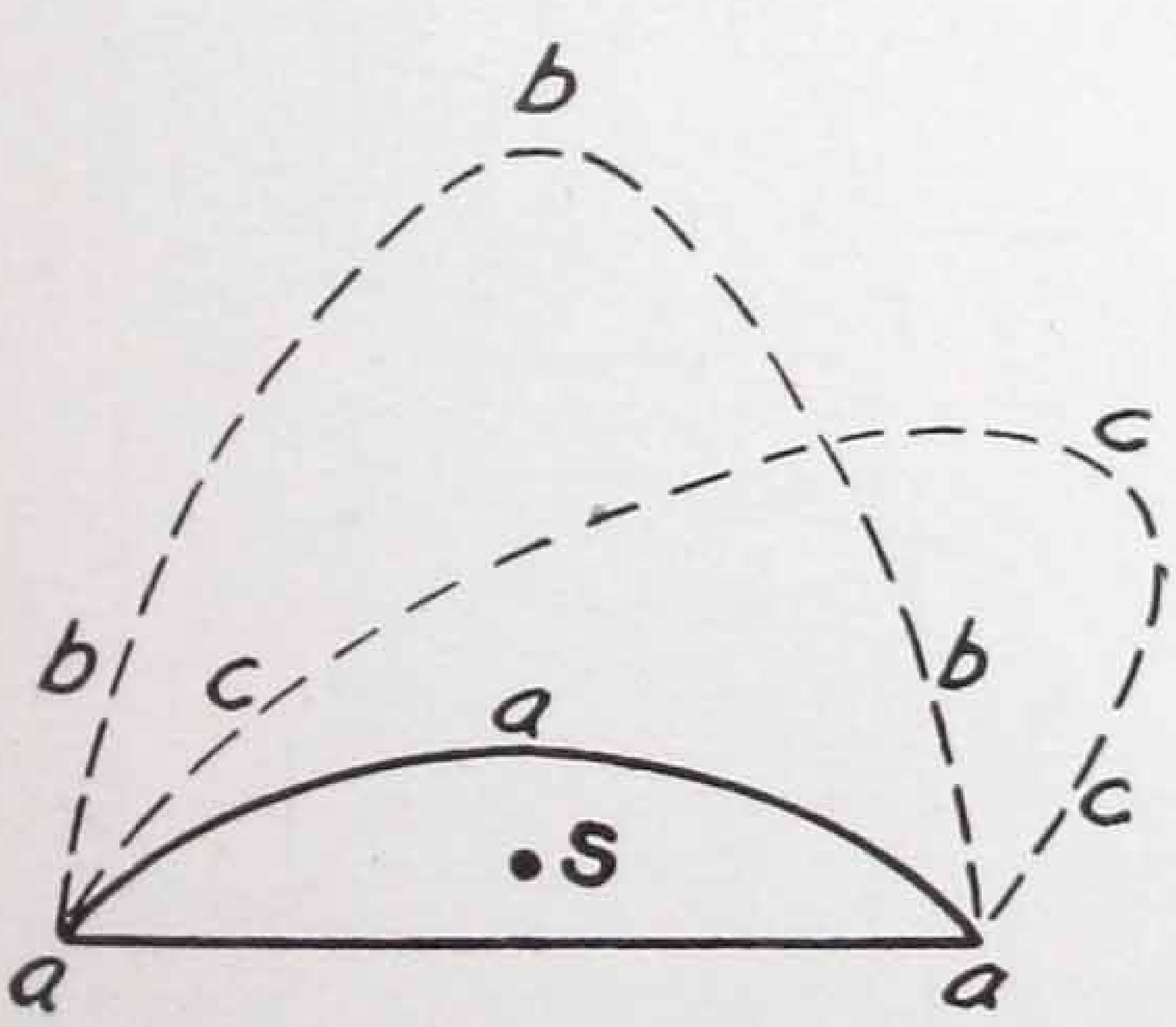


Fig. 23—The shape of a rough-surface reflector has relatively little effect on distribution

Since light which falls upon a rough or mat surface is reflected in all directions, it follows that the shape of reflectors with such a surface can have but little effect on the resulting distribution of light. In Fig. 23, *S* represents a light source at the mouth of a rough-surface reflector *aaa*. The light distribution is the same when the reflector has

the cross-section *aaa*, *bbb*, or *ccc*, for when the reflector is viewed from below, it simply appears as a white disk. However, if a contour such as *bbb* or *ccc* is used rather than *aaa*, there will result a needless absorption of light due to cross reflection; the light from *S* is utilized to better advantage with the shape *aaa*.

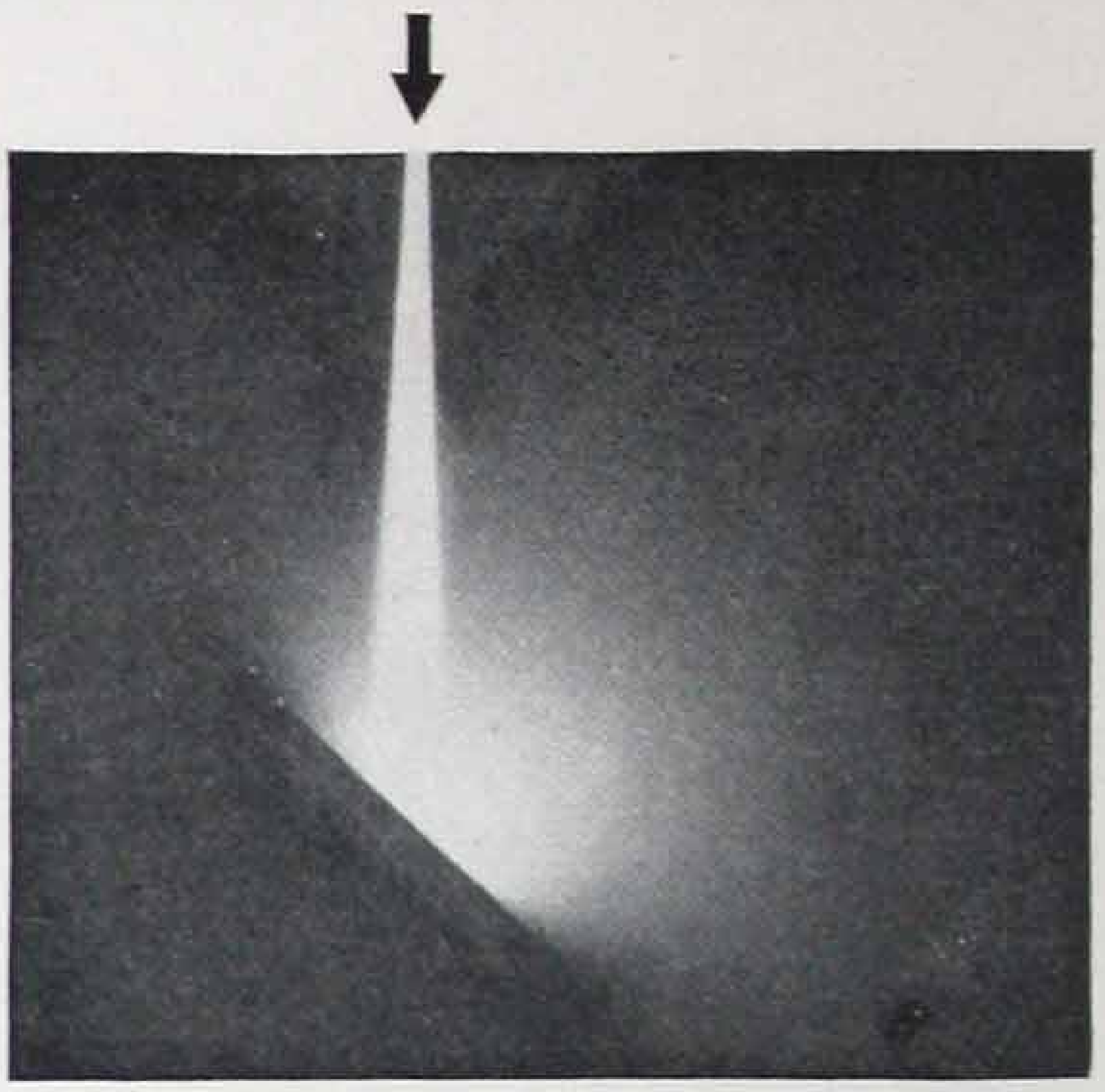


Fig. 24—Reflection from rough-mat surface—blotting paper

It is more difficult to keep mat-finish surfaces clean than those with a glaze or polish and therefore such rough surface finishes are not widely used for luminaires. However, surfaces such as plaster, kalsomine, and wallpaper have all of the characteristics of mat-surface reflection, in fact when they are examined minutely they reveal an extremely rough contour. Most of the light received from the walls and ceiling of a room is by diffuse reflection.

Clear Glass Surfaces

When a light ray strikes a plate glass vertically about 4 per cent is reflected from its upper surface and about 3 or 4 per cent from its

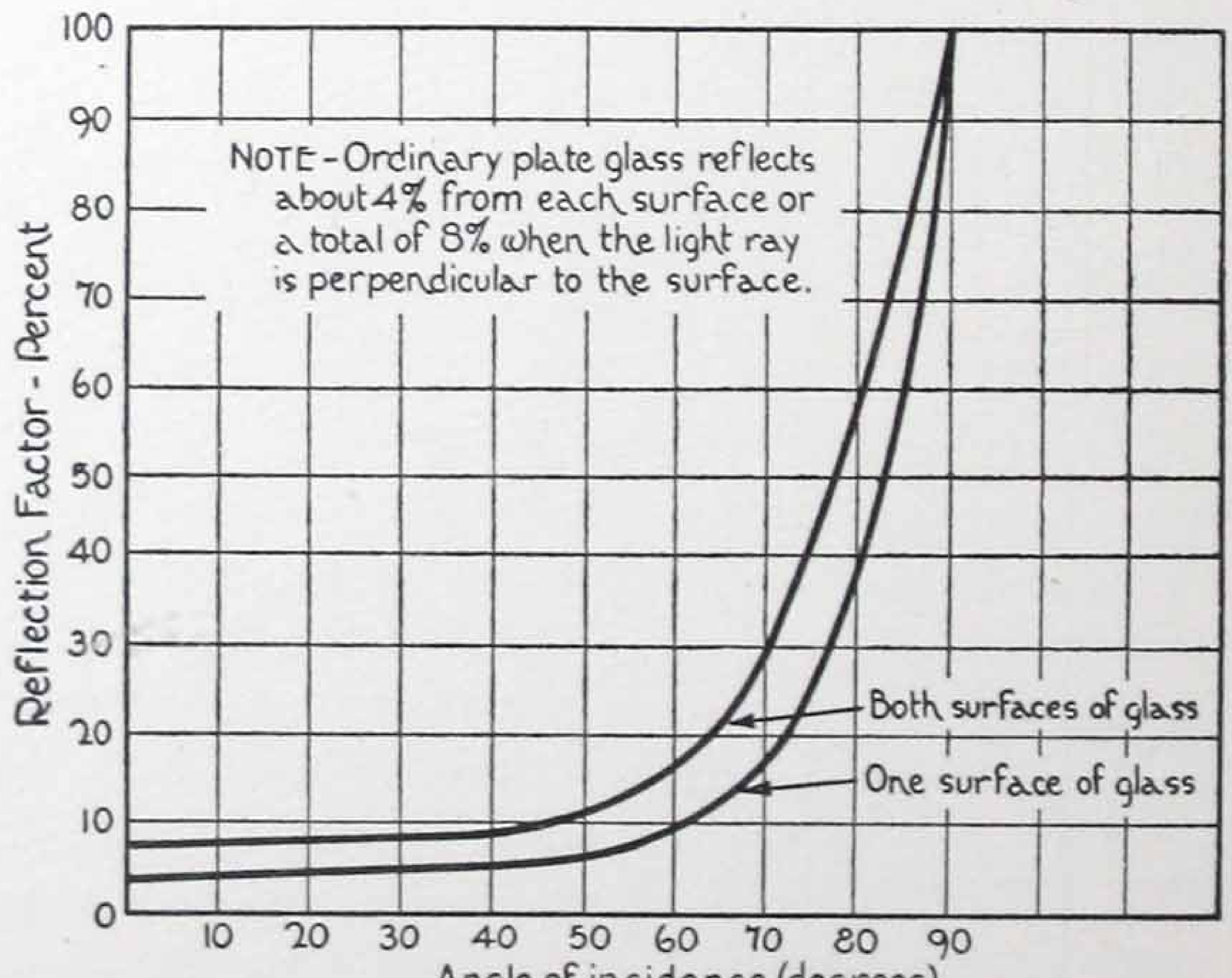


Fig. 25—Reflection of light from clear plate glass, angle measured from perpendicular as X, Fig. 18.

lower surface; the remaining light being transmitted (approximately 85%) and absorbed (5 to 8%). When light strikes glass at an angle two phenomena occur, first, the percentage of light reflected from the upper surface increases markedly so that at 85 degrees, for instance, very little is transmitted, nearly all is reflected; second, light rays in passing through the glass are bent toward the perpendicular. Figure 25 gives the percentages of reflected light for all angles of incidence.

When a light ray passes from air to another more dense medium, such as water or glass, all parts of the face of the light beam do not enter the medium at the same time (Fig. 26). Thus, the part of the beam at *f* enters before the part *c*, and it is slowed up. As a consequence the wave is swung around or refracted to the position *B-C* in the water. The extent of this refraction depends upon the ratio of the velocities of the light as it passes through the two media.

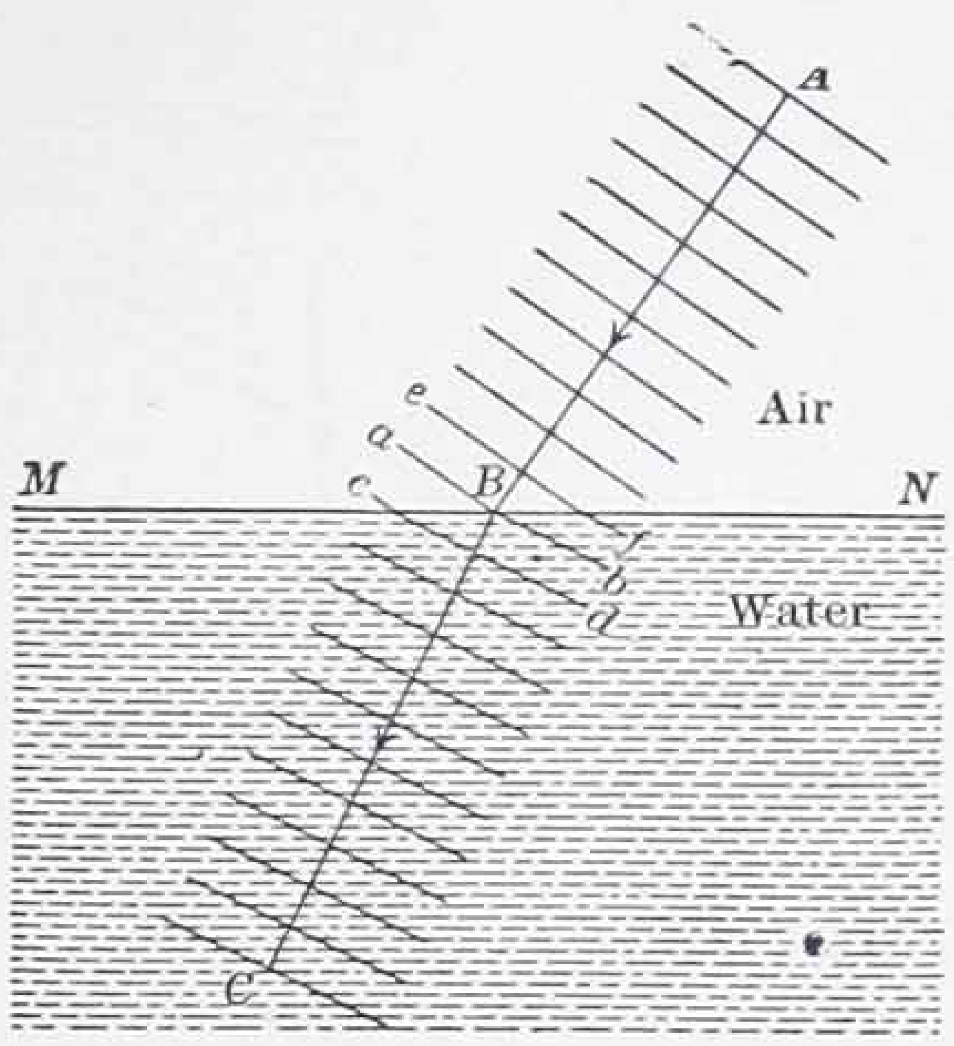


Fig. 26—Diagram of light beam subject to refraction

Gloss Finish Paints

Not infrequently plastered walls and similar surfaces are finished with a gloss or enamel paint, and as a consequence the collection of dust and dirt upon the surfaces is minimized. Such surfaces have a noticeable sheen, that is, they have bright reflections of the sun or other sources of light. For this reason, it is likely to appear that their reflecting qualities are similar to those of polished metal or at least like aluminum paint, rather than diffuse reflection. The specular reflection from such glossy surfaces, however, represents only a small part of the incident light.

Painting with enamel paints is similar to putting clear glass over a mat-finished wall. The light reflected from the glass would give brilliant images, but represents only 5 to 15 per cent of the total, the greater bulk of the reflected light being diffusely reflected from the mat surface beneath.

White or Milk-Glass Reflecting Surfaces

White (loosely termed opal) glass finds considerable application in illumination, primarily to reflect or to diffuse light. The properties of white glass may be most readily understood if we regard it as ordinary glass in which fine white particles are held in suspension. When a ray of light strikes a piece of white glass, 10 to 15 per cent of it is reflected at once from the polished surface of the glass without entering the glass at all, the remainder traveling through the glass until it strikes the white particles whence it is dispersed in all directions, some of it being thrown back and reflected, as shown in Fig. 27.

If any light ray passes through the glass without striking a white particle, it goes out in a line parallel to the one along which it entered. When this occurs, the white glass is not completely translucent, and if,

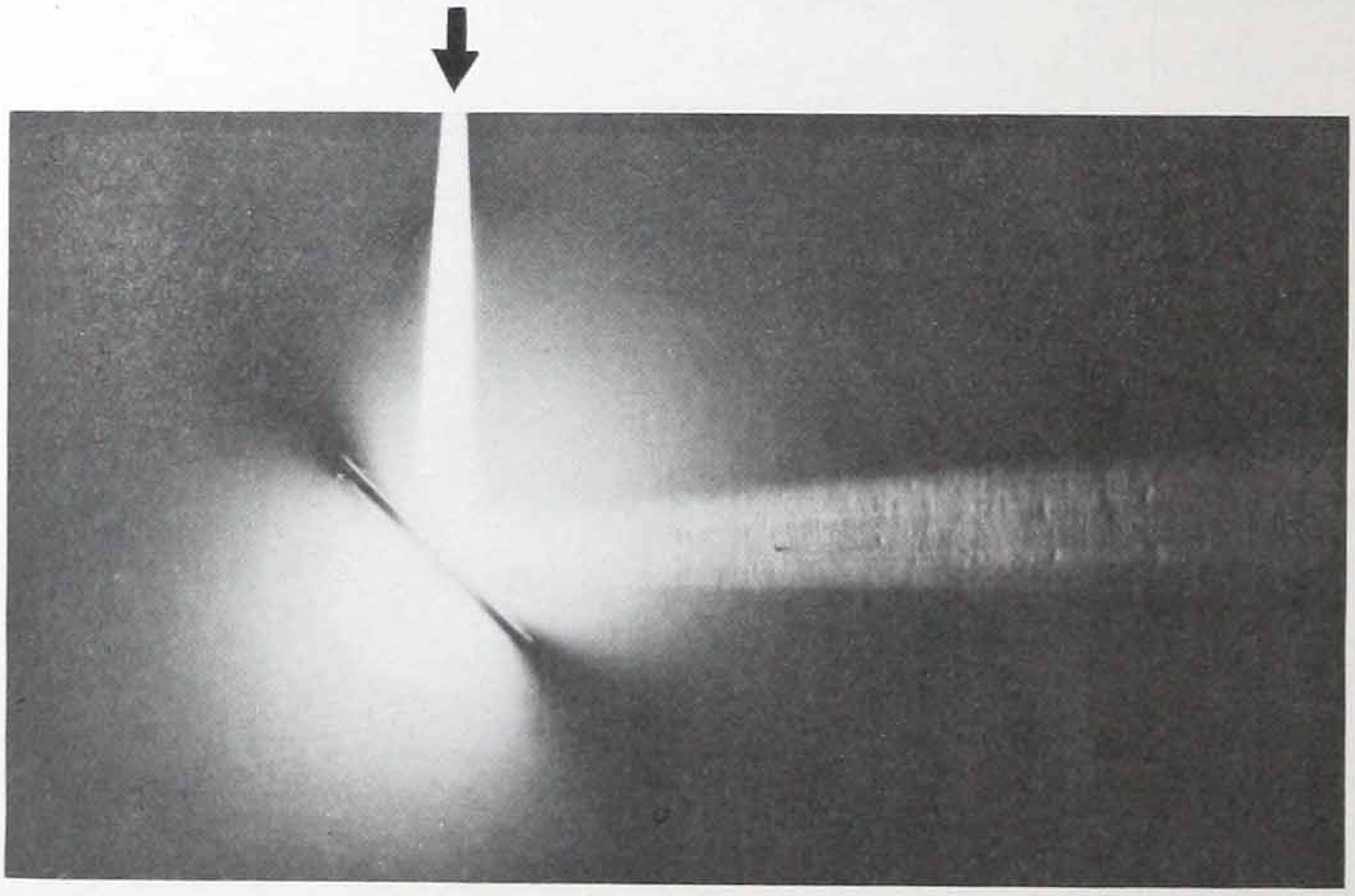


Fig. 27—Reflection and transmission by white or milk glass

for example, it is in the form of a globe, the outline of the lamp filament could be seen more or less clearly. This condition would be present even though only one per cent of the light passed through unchanged, as shown in Fig. 28.

When it is desired that the reflecting qualities predominate, a very dense white glass should be chosen, that is, one which transmits not more than 10 to 15 per cent. Such a glass would probably absorb 15 per cent, and reflect 65 per cent. If diffusion is the main objective, as

in the enclosing globe type of luminaire, the glass should have a maximum transmission without revealing the outlines of the light

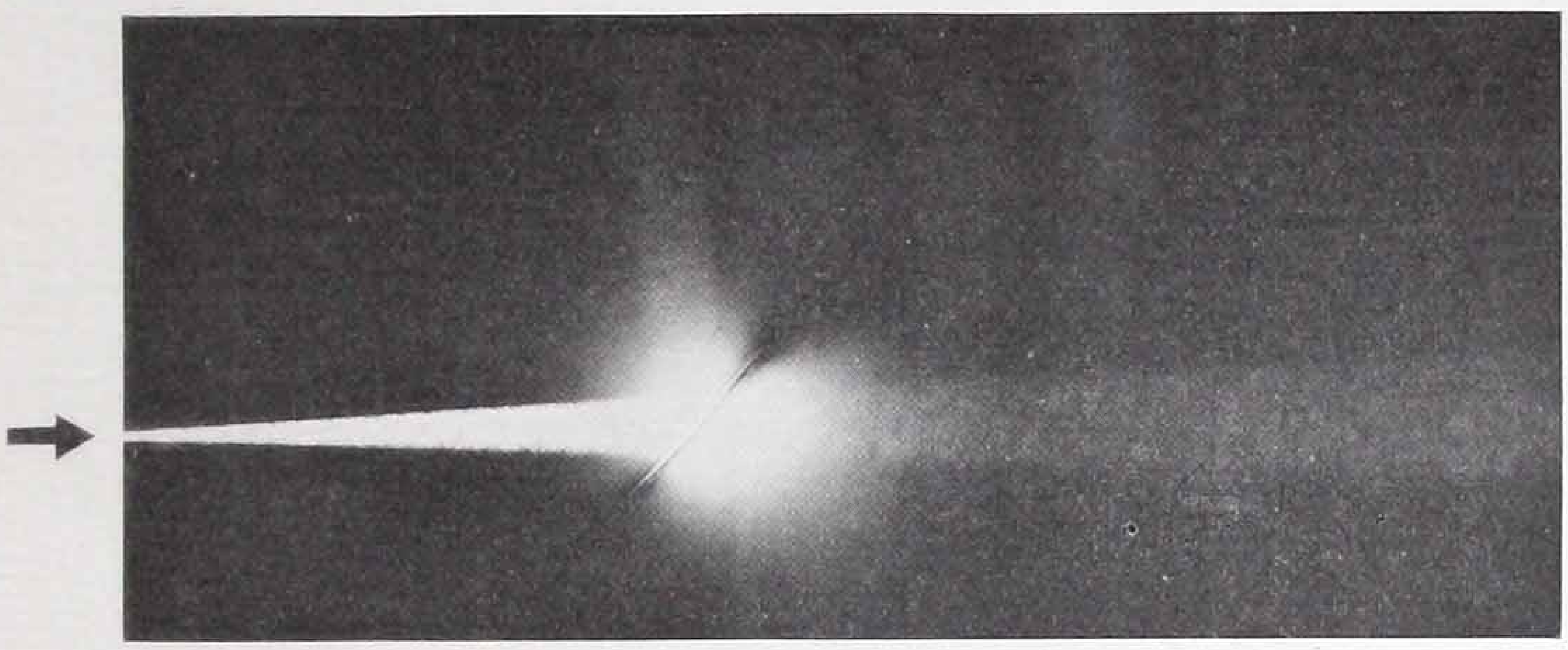


Fig. 28—Transmission and reflection of white glass (very light sample)

source. This limits the transmitted light to about 50 or 60 per cent. A totally enclosing white-glass ball may, however, have an over-all output as high as 85 per cent, for while only 55 per cent of the light coming from the lamp may be transmitted directly through the glass, sufficient light may come from the interior by cross reflection to bring the output up to 85 per cent.

This may be explained as follows: Assume a source of 100 lumens placed in the center of a glass sphere as shown in Fig. 29. Assume that the glass transmits 55% of the light, absorbs 10%, reflects 35%. Then since 50 lumens strike the upper half of the sphere, 27½ lumens would be transmitted, 5 lumens absorbed, and 17½ lumens reflected to

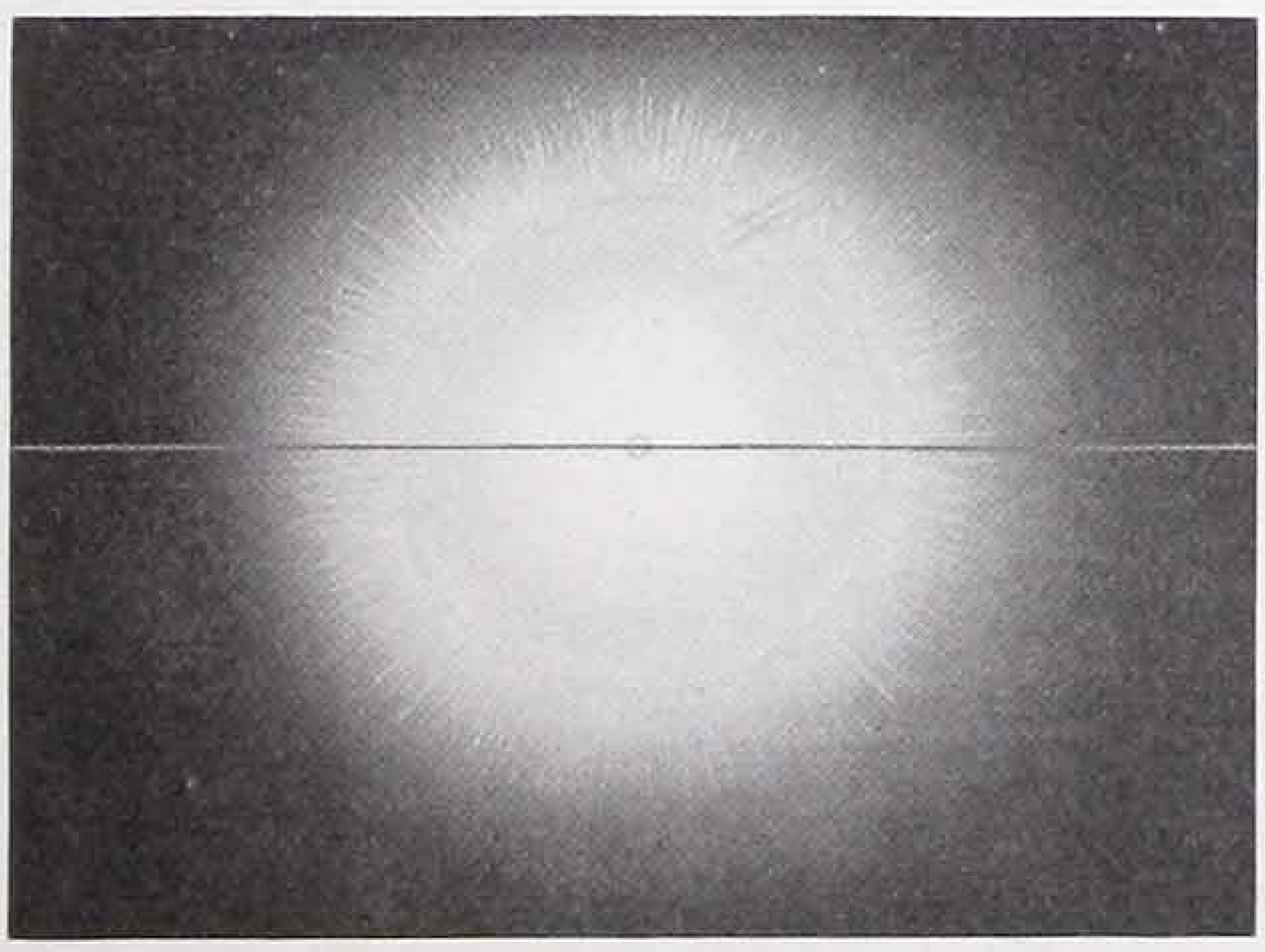


Fig. 29—Spherical white-glass unit (see above)

UPPER HALF				LOWER HALF		
Lumens Absorbed (10%)	Lumens Transmitted (55%)	Lumens Reflected to Lower Half (35%)		Lumens Reflected to Upper Half (35%)	Lumens Transmitted (55%)	Lumens Absorbed (10%)
5.0	27.5	17.5		17.5	27.5	5.0
1.7	9.6	[6.2]		[6.2]	9.6	1.7
0.6	3.4	[2.2]		[2.2]	3.4	0.6
0.2	1.2	[0.7]		[0.7]	1.2	0.2
....	....	....		....	....	....
7.5	41.7+			41.7+		7.5

the lower half of the sphere. Of these 17½ lumens, in the same way, 9.6 lumens are transmitted, 1.7 absorbed, and 6.2 again reflected upward. Of these 6.2 lumens, 3.4 are transmitted, 0.6 absorbed, and 2.2 reflected. The 50 lumens of the lower half of the sphere are distributed in the same manner. If the calculations are carried out far enough it will be found that the transmitted light for each half is about 42.5 lumens, making a total output of 85 per cent. The values are given in the table above.

Two-piece glass units are frequently made with the upper section larger than the lower section, and the upper section made of denser glass to reflect a maximum amount of light downward. A unit of this character may similarly be investigated. Assume that the upper section

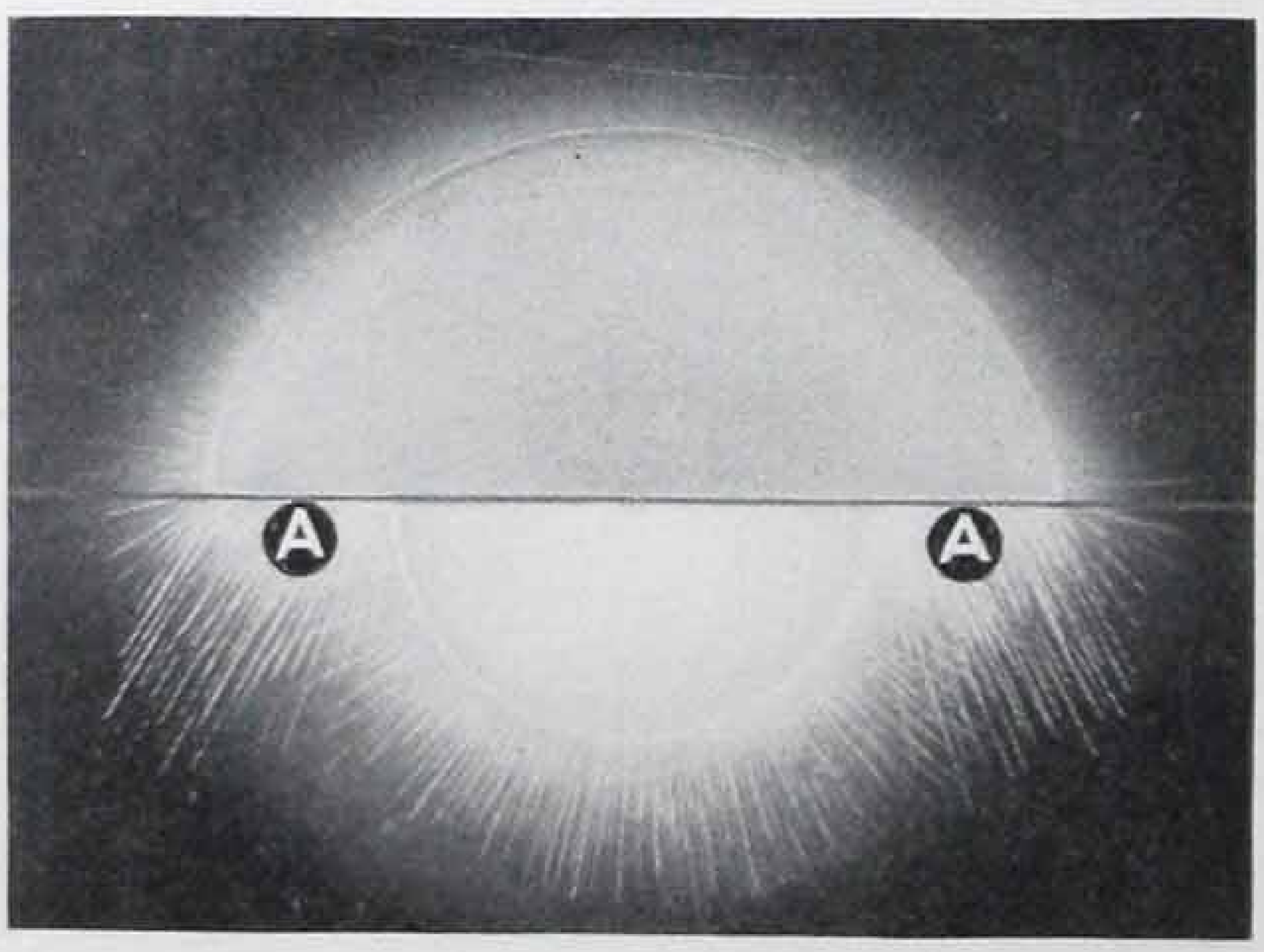


Fig. 30—Dense and light white-glass unit (see next page)

WHITE OR MILK-GLASS REFLECTING SURFACES

UPPER HALF				LOWER HALF		
Lumens Absorbed (15%)	Lumens Transmitted (20%)	Lumens Reflected to Lower Half (65%)	Lumens through A	Lumens Reflected to Upper Half (35%)	Lumens Transmitted (55%)	Lumens Absorbed (10%)
7.5	10.0	32.5	(16.2)	17.5	27.5	5.0
2.6	3.5	[11.4]	5.7	[5.7]	8.9	1.6
0.9	1.1	[3.7]	1.8	[2.0]	3.1	0.6
0.3	0.4	[1.3]	------	[0.6]	1.0	0.2
....	....	....	....	....	....	....
11.3+	15.0+		23.7+		40.5+	7.4+

is about twice the size of the lower and is of dense glass which absorbs 15%, transmits 20%, and reflects 65%, the lower section being of lighter glass of the characteristics of Fig. 29. The source is again 100 lumens. Of the 50 lumens going to the upper half, 10 lumens are transmitted, 7.5 absorbed, and 32.5 reflected downward. Since the section at A is open and is about half the area, 16.2 lumens pass on out. The other 16.2 lumens enter the lower hemisphere where, because of the light density of the glass, 8.9 lumens are transmitted, 1.6 absorbed, and 5.7 reflected again to the upper half of the unit. Of the 50 lumens of the lower half, 27.5 are transmitted, 5 are absorbed, and 17.5 reflected to the upper zone. By following the calculations through, it may be seen that the transmitted light through each of the hemispheres added to the light that comes out at A, totals about 80 per cent, for the over-all output of the glass.

In this manner the effect of variations in the quality of glass, shapes and sizes of luminaires, and other factors and characteristics of glassware may be studied and demonstrated.

Two important advantages make white glass a very desirable reflector material. These are: (1) its smooth surface minimizes the collection of dust and permits easy cleaning; and (2) the glass transmits a portion of the light, which renders the reflector luminous and thereby adds materially to its appearance. These two advantages are largely responsible for the wide use of white glass for illuminating purposes.

White glass is used for open reflectors, semi-enclosing units, for enclosing luminaires, and for semi-indirect units for schoolrooms, offices, general commercial application, and for certain types of industrial luminaires.

Contour of white glass luminaires is a less important factor than in the design of mirrored glass reflectors, and is determined largely by the appearance desired. In semi-indirect lighting one of the main advantages of using white glass is in the possibility of reducing the brightness of the light source so that it is comparable with its surroundings; care should be taken in the selection of such units, particularly for offices, schoolrooms, and the like, to choose a sufficiently dense glass.

Porcelain Enamel Reflecting Surfaces

In the familiar enameled-metal reflector, the surface, so far as its optical characteristics are concerned, can best be considered as a plate of white glass in optical contact with a steel backing. The glass must

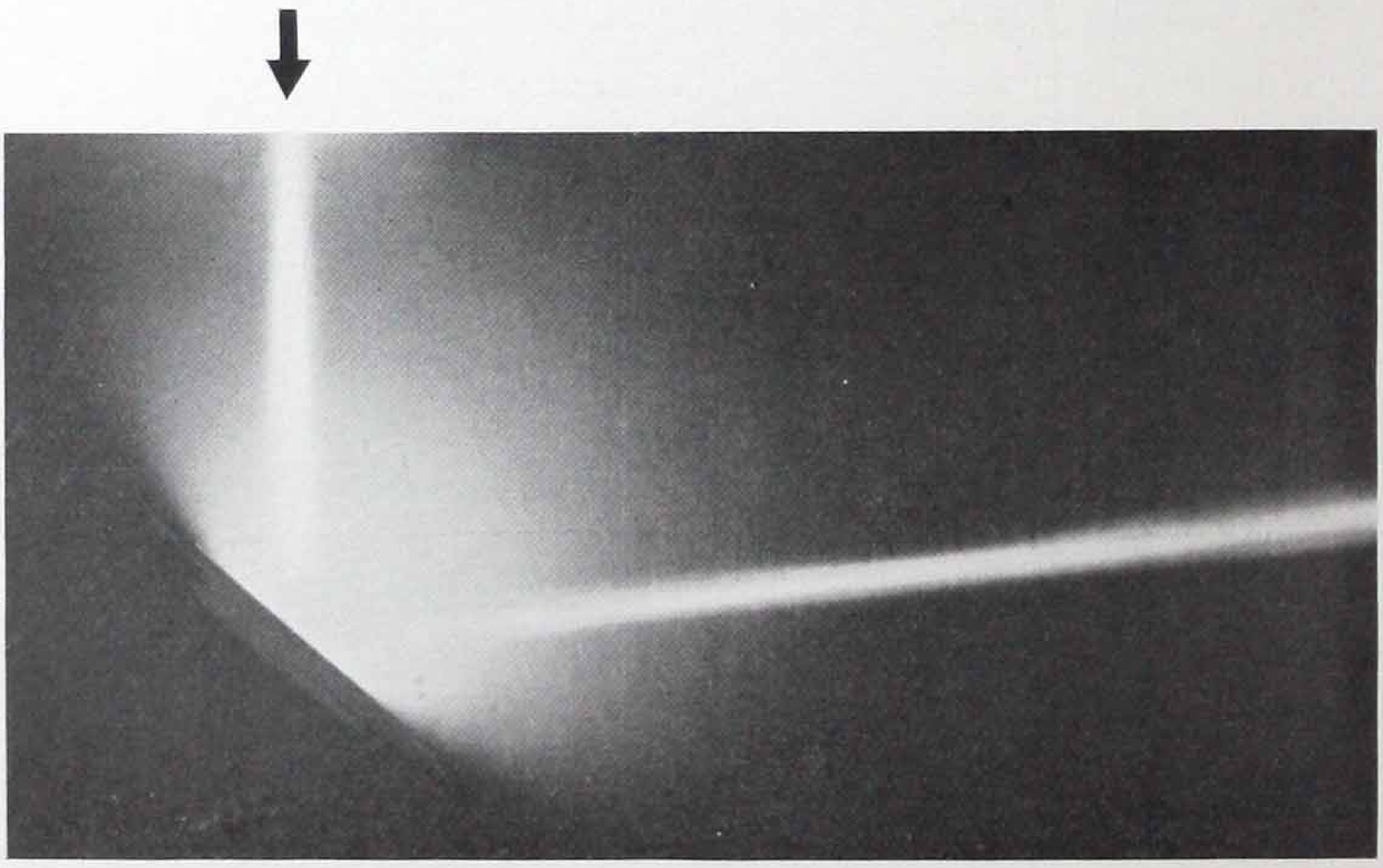


Fig. 31—Reflection by porcelain-enameled steel

be very dense so that as little light as possible will pass through, for all the light that penetrates to the steel backing is absorbed, and therefore wasted. Porcelain enamels vary considerably in efficiency; if of two reflectors one appears gray in comparison to the other, it is

sure to be considerably lower in efficiency. Figure 31 shows the characteristic reflection of a porcelain-enameled surface on steel.

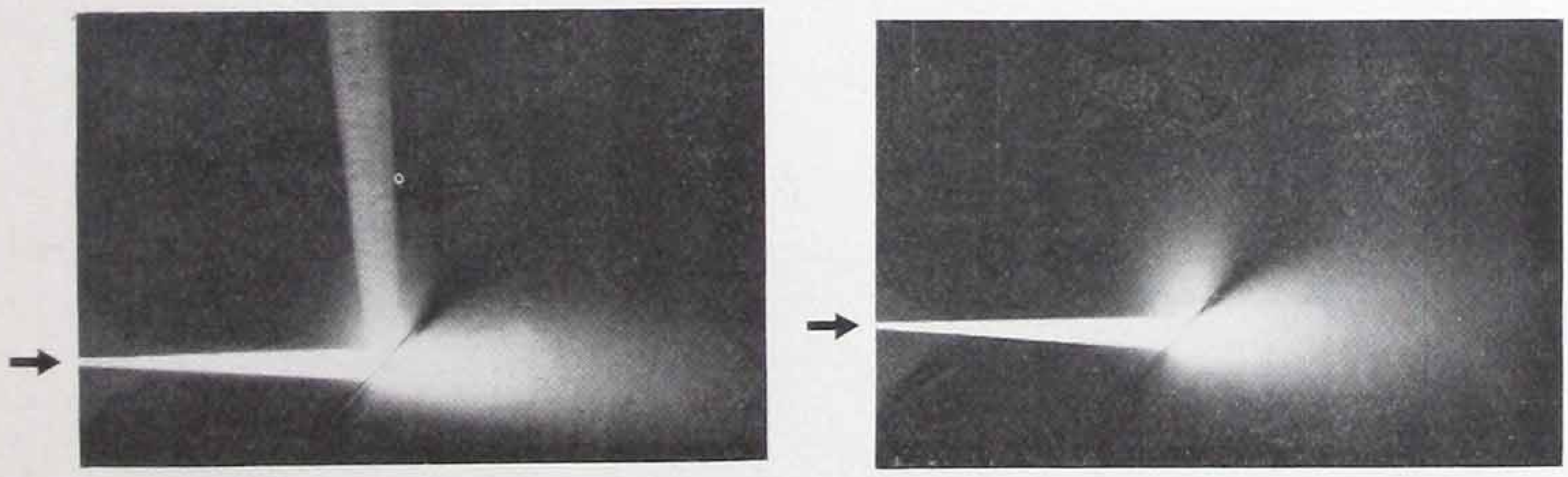
Probably the first thing that is noticed in Fig. 31 is the beam of regularly reflected light. This is simply specular reflection from the glazed surface, and, as in the case of white glass or glossy paint, does not ordinarily amount to more than 5 to 15 per cent of the incident light. By far the greater proportion is diffusely reflected as shown and therefore porcelain enamel reflectors are subject practicaly to the same design limitations as were outlined in the discussion of rough or mat reflecting surfaces.

Reflector designers have frequently been deceived by the shininess of porcelain enamel, into believing that light would be as readily controlled by it as by a mirror, and they have consequently often been disappointed in the results.

Porcelain enamel steel reflectors find their principal use in industrial lighting, where the advantage of efficiency, ruggedness, and permanency of reflecting surface are important.

Frosted-Glass Reflecting Surfaces

Frosted-glass transmission characteristics may be compared to the reflection characteristics of an unpolished metal surface. Fig. 32 shows the direction of a beam of light striking glass, one surface of which is smooth and the other surface sand-blasted or roughened with acid etching. Some of the light is, of course, reflected from the glass as is shown in



Smooth side toward beam   Frosted side toward beam

Fig. 32—Reflection and transmission by etched glass

the figure, but most of it goes through the glass and as the individual rays strike the rough surface they are partially dispersed.

Etched glass should be used to give a spread transmission of light rather than as a good reflector. It is of little value except for enclosing

units. Unless a frosted glass surface is of a very fine texture, it accumulates dirt rapidly and is difficult to clean.

A recent tendency in illuminating engineering has been to make use of stippled or pebbled glass which has the diffusing characteristics of sand-blasted glass without the same difficulty of cleaning. Glasses of this character are especially valuable where it is desired to transmit light without greatly changing its direction, such as in the outer globes of street lighting units.

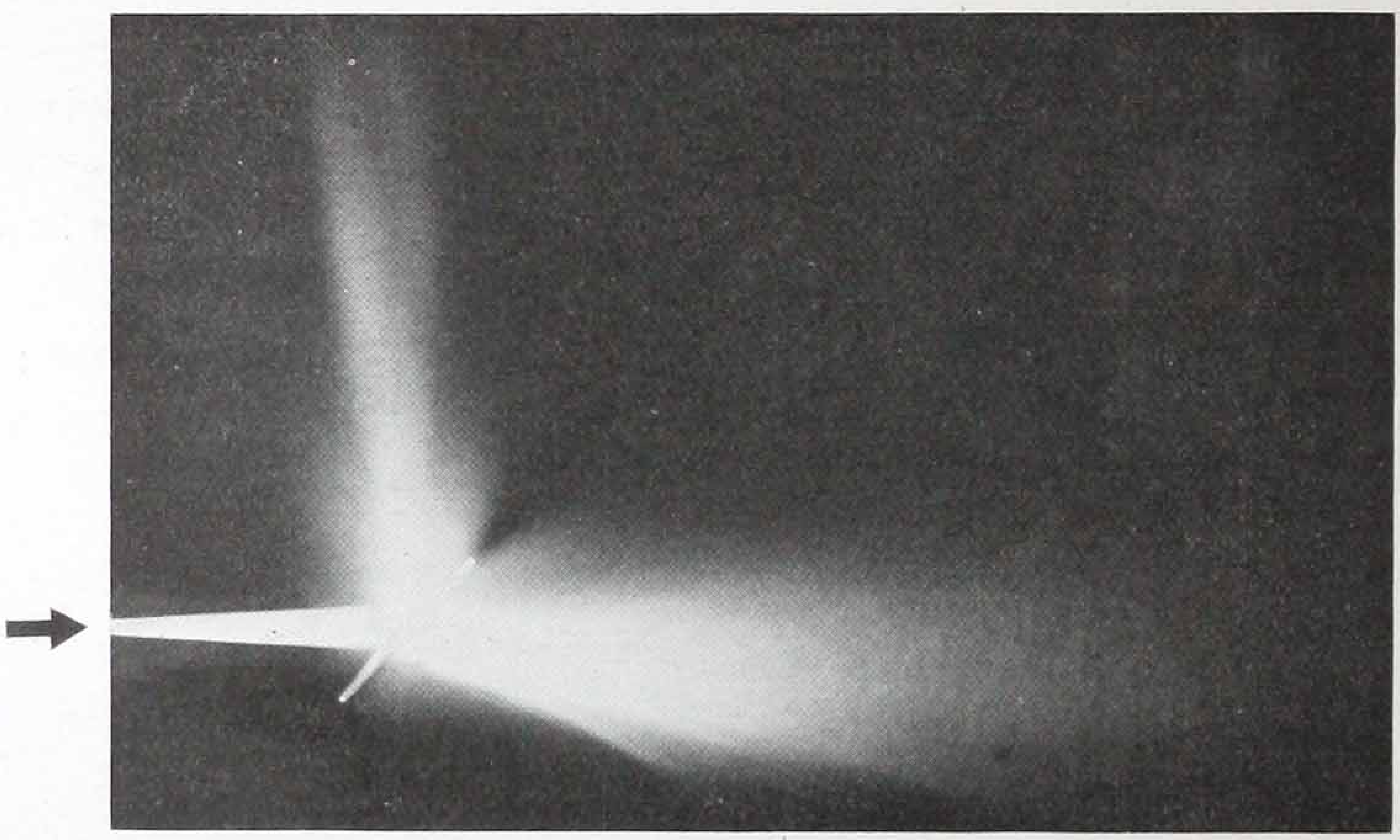


Fig. 33—Characteristic distribution of clear rippled (or pebbled) glass—smooth side toward beam

Prismatic Refractors

On page 30 it was shown that when a light ray enters a glass surface obliquely, it is bent toward the perpendicular. The reverse occurs when it leaves, as though the ray were coming up from the water in Fig. 26, moving away from the perpendicular. As has been stated, a ray of light passing through a flat plate of glass will leave in a line parallel to the one on which it entered. If the two sides of the glass are not parallel, as in the case of the prism a more pronounced effect is secured, as shown in Fig. 34.

Refracting prisms of this type find application wherever it is desired to produce a very broad distribution of light, for example, in street lighting units, in railway and traffic signals, and Fresnel lenses as used in lighthouse service.

Prismatic Reflectors

Since light rays emerging obliquely from a dense medium, such as glass, are bent down toward the outer surface of the glass, there exists a critical angle at which the light will not leave at all but will be refracted along a line parallel with the glass. At angles greater than this critical angle, the rays are reflected internally, as though the surface were a mirror; for crown glass this angle is about 43 degrees.

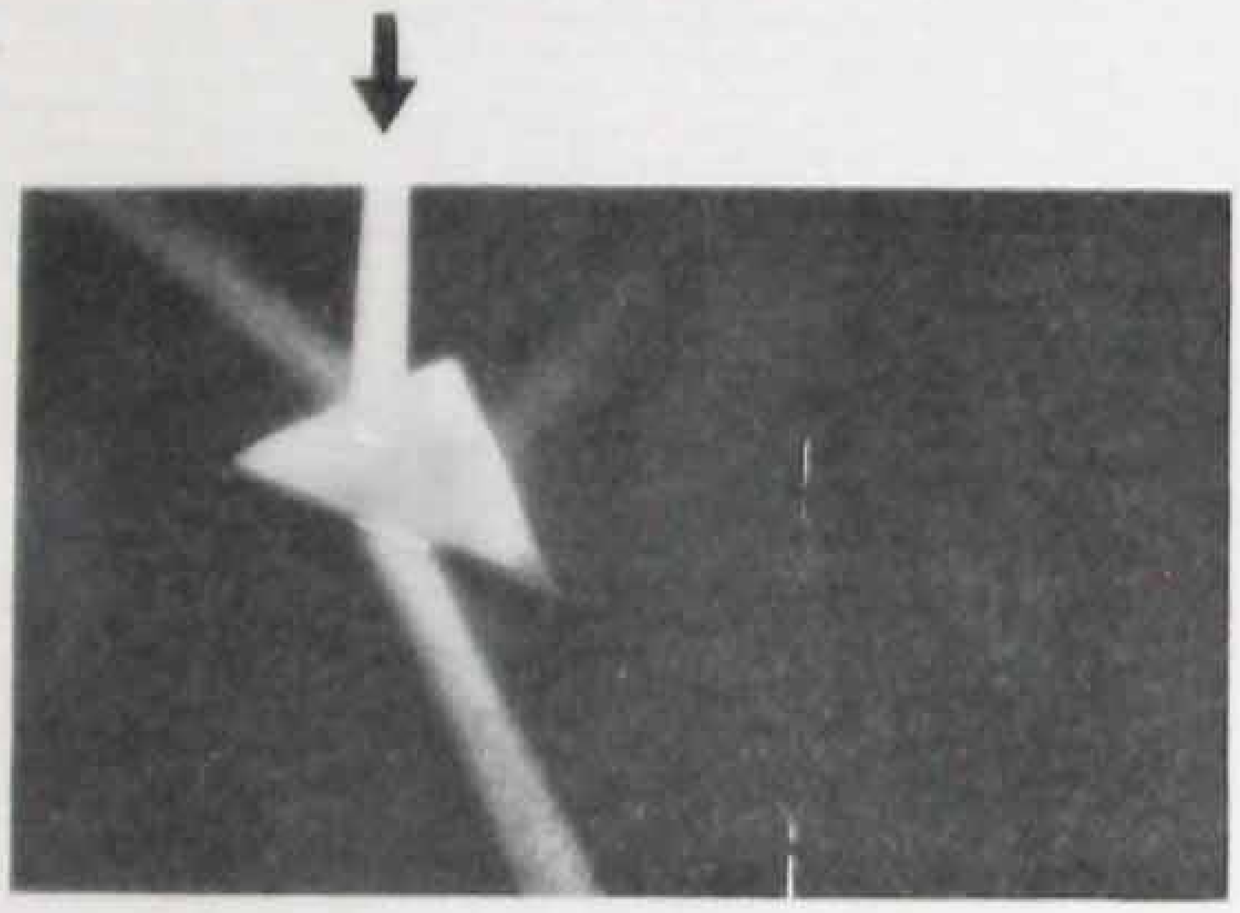


Fig. 34—Refraction by prism

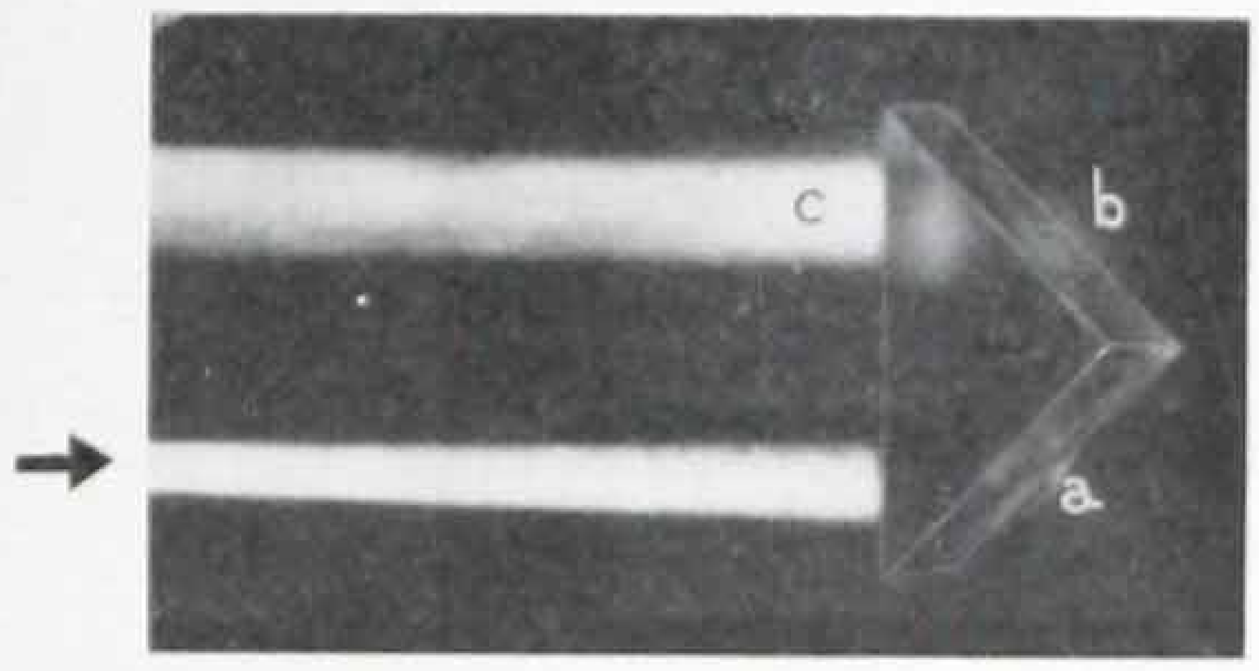


Fig. 35—Total reflection by prism

Total reflection can be accomplished by means of a prism, through "double" reflection. As shown in Fig. 35, the beam enters the diagonal face of a right-angle prism, travels straight through the glass to the short face *a*, which is strikes at about 45°, is directed by total reflection to the face *b*, leaving the prism at *c*, substantially parallel to the entering beam. This is the principal used in prismatic glass reflectors. Reflecting prisms are customarily designed so that the light strikes at about 45 degrees (90° prisms).

Many direct and semi-indirect types of lighting equipment for offices, schools, and public buildings, are of prismatic glass.

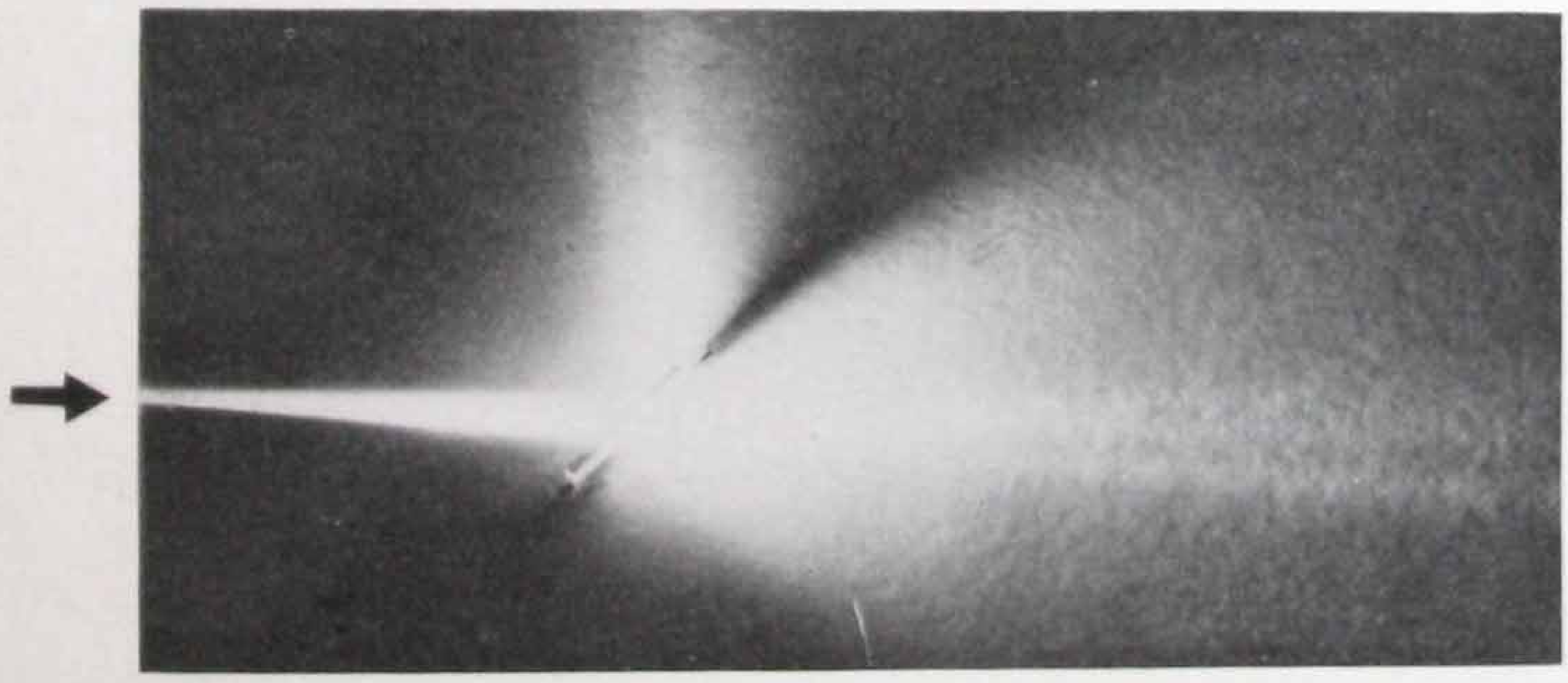


Fig. 36—Reflection and refraction by factory rib glass

Factory rib glass, commonly used in industrial plants, spreads out the light, as shown in Fig. 36.

Part III—Essentials of Modern Illumination

THE foregoing studies of the measurement of light and the means by which light may be controlled are fundamental concepts—an important background for understanding the more practical features of planning a lighting system which will banish gloom and glare and safeguard vision and eyesight.

Illumination, distinct from raw light, involves a consideration of: first, *quality* as regards diffusion, distribution, and color value; second, *quantity*, as concerns the actual physical process of vision and the psychological reaction of light to cheer, and to comfort the senses.

QUALITY OF ILLUMINATION

Quality of illumination refers to the general lighting effect, analyzed according to general or to specific requirements, and its suitability with respect to the requirements it is called upon to meet. Some factors such as glare are always undesirable and should be avoided under all circumstances. On the other hand, proper color of light can be obtained only by a knowledge of the conditions to be met. For example, light modified to produce "warm" tones for decorative effect would be out of place in a lithographing plant where the white quality of daylight is essential for properly judging the color of pigments. Such factors are discussed more fully below.

Glare

Glare is any brightness within the field of vision of such a character as to cause annoyance, discomfort, interference with vision, or eye fatigue. It might be called "negative" light or light out of place. Glare may be direct or reflected, that is, it may come directly from the light source to the eye, or it may be reflected brightness such as from a desk top, nickeled machine parts, or calendered paper.

Direct glare from a light source is the more common, and is more often a hindrance to vision. A glance at the sun proves that an extremely bright light source is capable of producing acute eye discomfort. Light sources of far less brilliancy than the sun, such as the filament of an incandescent lamp, or the incandescent mantle of a gas lamp, are also quite capable of producing discomfort by direct glare.

Glare and Background Brightness

The extent to which glare is objectionable is partially dependent upon the contrast in brightness between the light source and the background. Automobile headlights on an unlighted highway, for instance, may be so glaring as to be blinding to the eye; the same lights in the daytime or on a well-lighted street would scarcely be noticed.

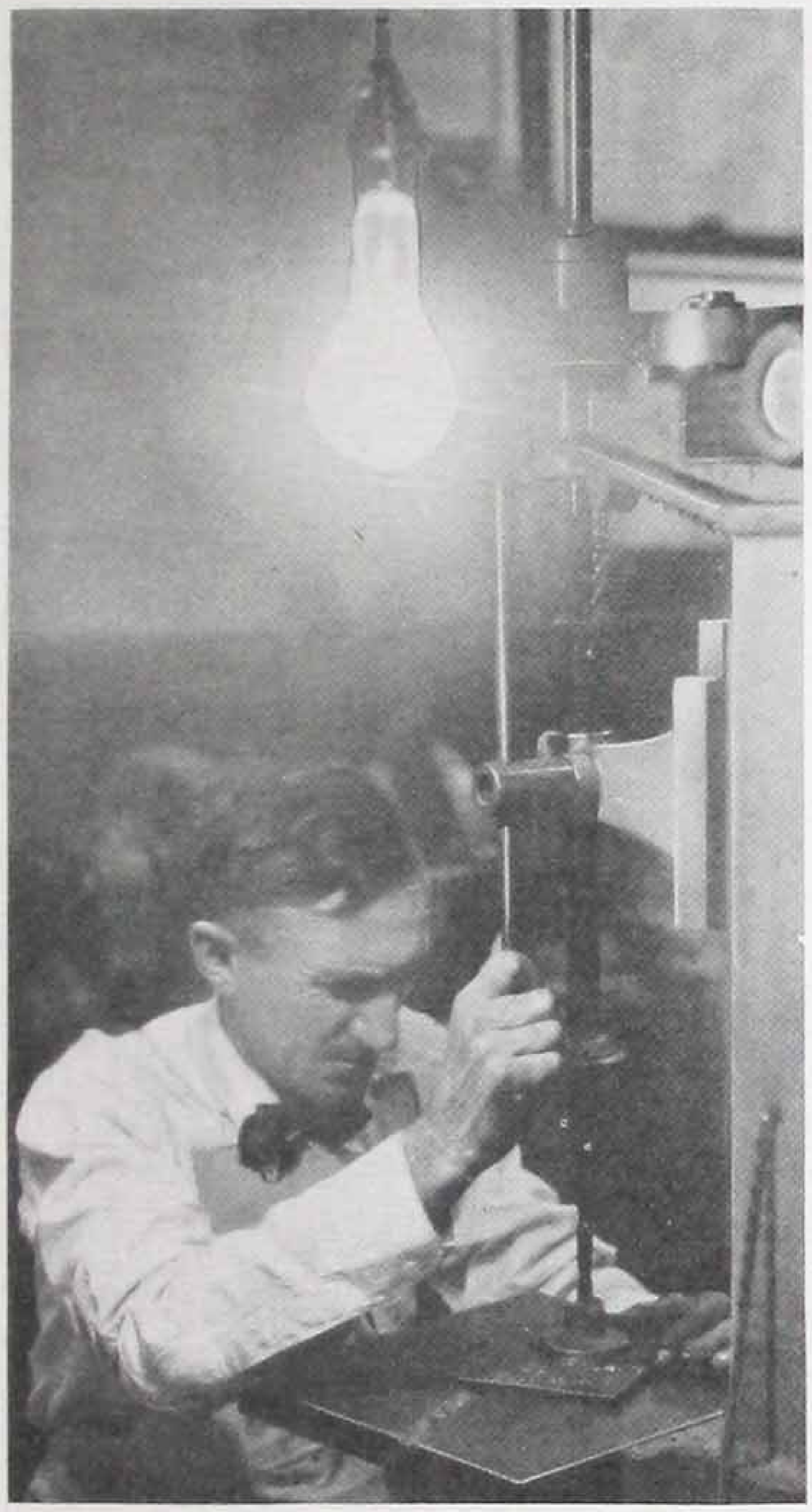


Fig. 37—Direct glare from a bare lamp is one of the greatest of hazards to vision. All lamps should be shaded.

Location in the Field of View

The effects of glare are dependent, also, upon the position of the light source in the field of view. In a shoe store, for example, the brightness of the lighting units is less of a problem than in a furniture store where rugs are displayed up high upon racks. Likewise, white or milk-glass enclosing luminaires may be sufficiently diffusing for a store, where people are continually moving about, whereas in a consultation room, the luminaires should be totally indirect or of a heavy density semi-indirect type.

Size of Light Source

The total candlepower of the light source, as well as the brightness of the source, is an important factor contributing to visual discomfort. For example, a 500-watt lamp in a 10-inch globe hung low within the field of vision is capable of causing acute visual discomfort. Screening three-fourths of the surface of the globe would very much reduce the glare, for by doing so, although the brightness in terms of candlepower per square inch is the same, the total candlepower toward the eye is reduced. Partially covering an enclosing globe with a shade, such as in the Glassteel Diffuser (page 55), accomplishes a similar purpose.

Degrees of Glare

There are two distinct "glare points" which are of particular interest in connection with artificial lighting. These values may be easily visualized by assuming an observer is looking at a 10-inch globe of white glass, containing a 500-watt lamp, which can be readily brightened and dimmed. As the candlepower of the lamp is raised, the globe reaches a point at which it appears just uncomfortably bright, when viewed casually against its background. Sources at or beyond this point in brightness should not be used for interior lighting of any class.

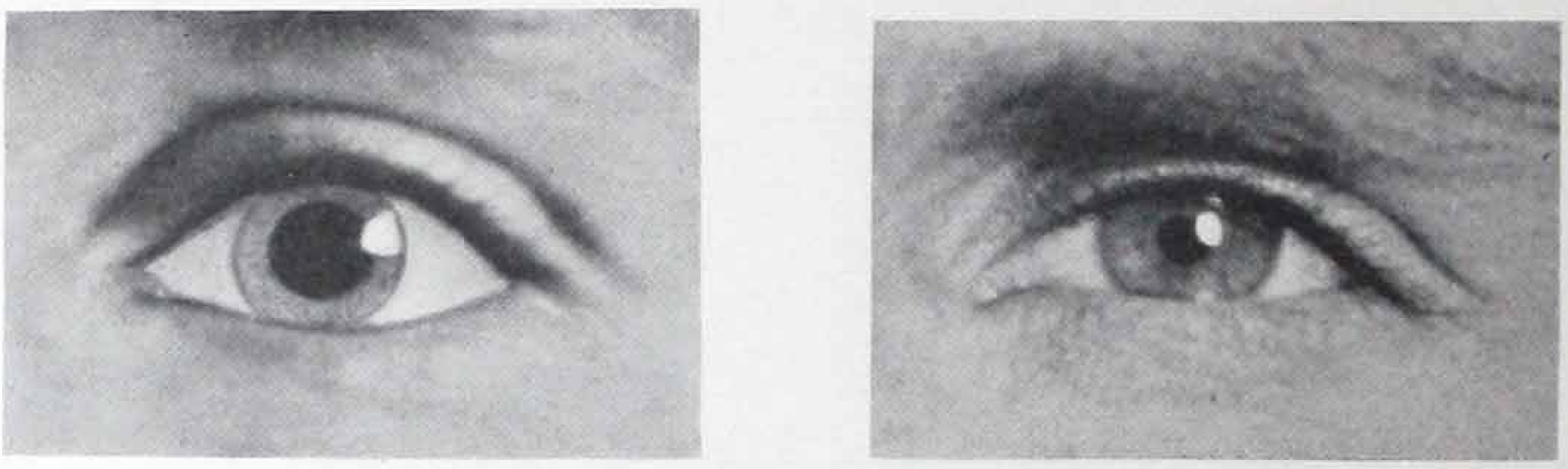


Fig. 38—The pupil of the eye contracts when a glaring light source is present

A second and much lower glare point is the brightness at which a source, not immediately recognized as glaring, proves trying and causes fatigue when it remains within the field of vision for considerable periods of time. This latter glare point is much more difficult to determine as it apparently varies through wide limits for different individuals. What this value represents may be more clearly understood by standing ten feet from a window, which by day, is the principal source of light for a room. Unless the room is very dark or the landscape very brilliant, the effect will not be at all unpleasant, but to sit all day facing such a window would prove extremely tiring, even if one were to sit at a desk or table and not pay particular attention to the window. Similarly, a light source which is not bright enough to cause an immediate sensation of glare may easily be too bright to be viewed continually with comfort.

Ordinarily the brightness of a lighting unit which is in the central portion of the visual field should not exceed from 2 to 3 candles per square inch of apparent area, if the unit is not to cause glare, and the brightness should be no greater than ½ candle per square inch of apparent area if it is not to fatigue the eyes when viewed continually. In this connection, it may be pointed out that the brightness of the sky rarely exceeds 3 candles per square inch.

A 200-watt lamp in a 10-inch white glass ball of medium density glass will emit light at an intensity of about 180 candles, the white glass ball diffusing the light to such an extent that the candlepower in all directions from the unit is approximately the same. The apparent area of the ball, 10 inches in diameter, is about 80 square inches; as one looks at the ball from a distance, a circular area is presented. The white glass ball is a source emitting $2\frac{1}{4}$ candles per square inch of apparent area. Such a unit would be too bright for an office, but would be satisfactory for hallways, store rooms, and similar places which are used intermittently, and for a large proportion of stores and industrial plants where those using the illumination are not called upon to face the luminaires for long periods of time.

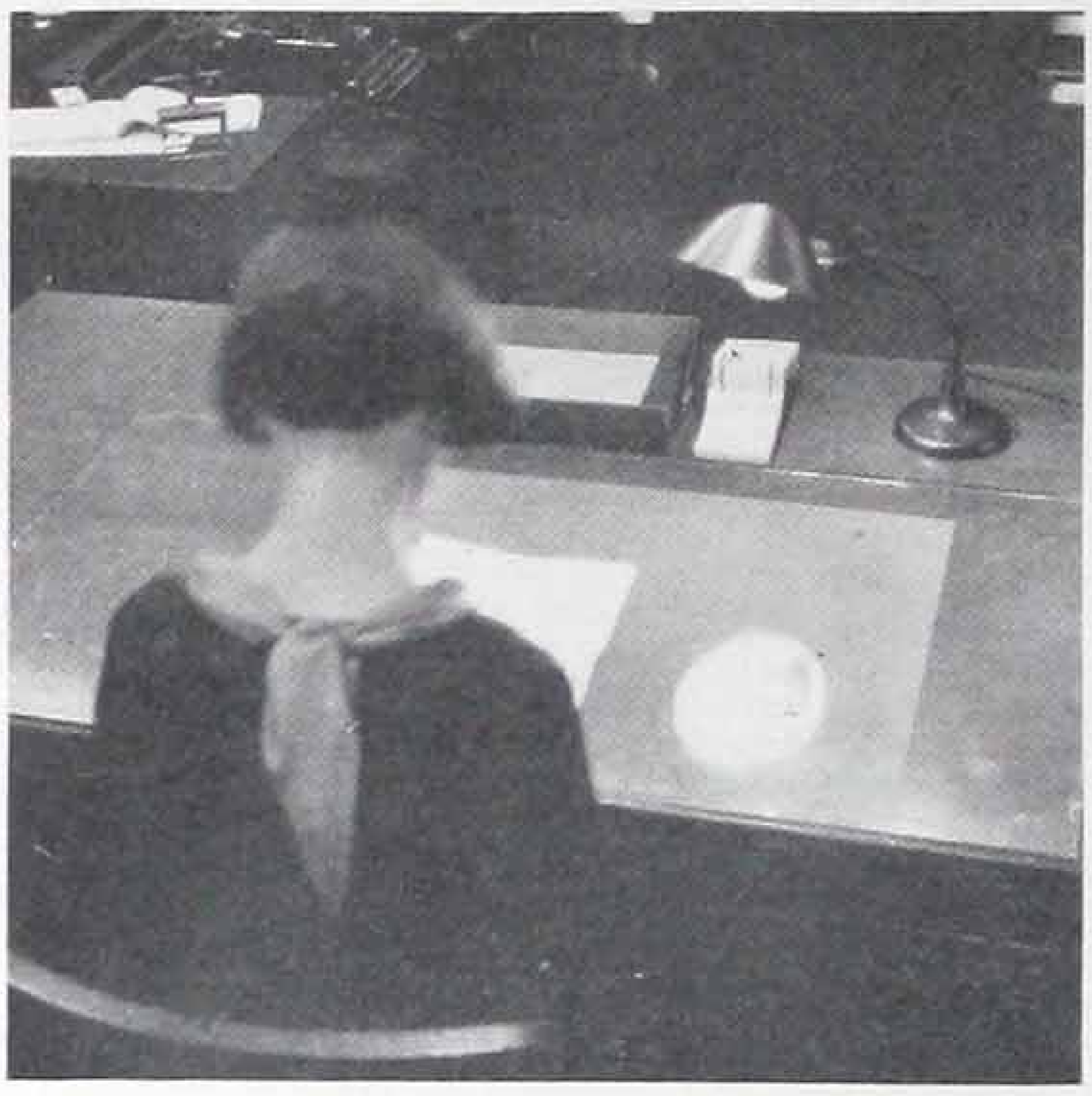
In order that this 200-watt lamp might be suitable for office lighting or similar locations where low brightness of the order of $\frac{1}{2}$ candlepower per square inch is essential, it would be necessary to use an enclosing globe of 360 square inches of apparent area or approximately 22 inches in diameter. A globe of such size is rather impractical and for that reason it is usually necessary to employ indirect or semi-indirect lighting in which case the light is directed over a ceiling area of many square feet, thus reducing the brightness of the apparent source.

It is logical, then, that as higher standards of illumination and larger size lamps are generally adopted, it will be necessary to consider more and more the necessity for indirect lighting as a means of keeping brightness of light sources within limits of comfort.

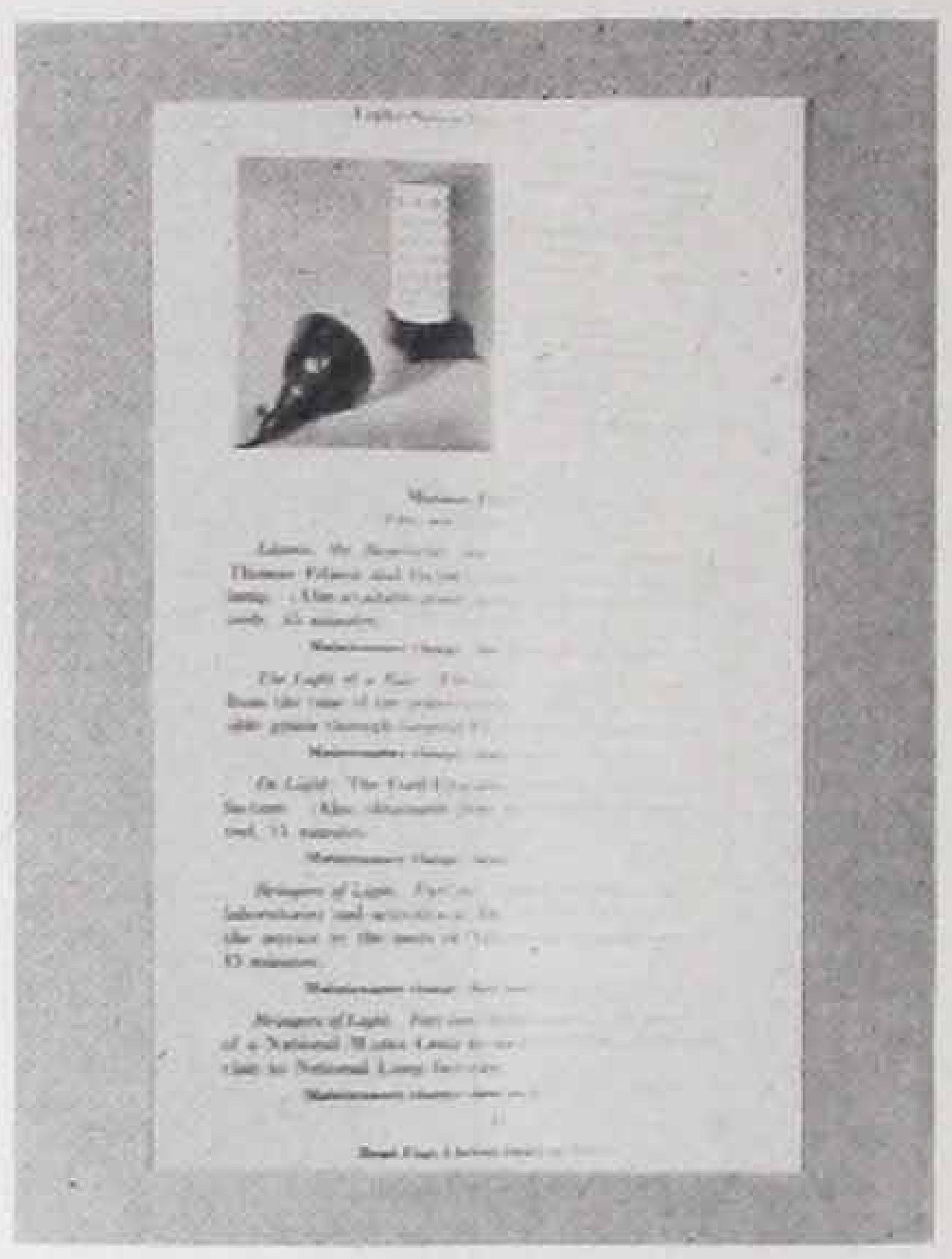
Reflected glare is glare which comes to the eyes as glint or reflection of the light source in some polished surface. It is often more objectionable than direct glare and quite frequently more harmful because of its insidiousness and because it is generally from a direction below the horizontal, a zone in which the eye has no natural protection. This form of glare, known as specular reflection or veiling glare, is frequently encountered when a person looks at glossy paper, polished metal or wood, or other shiny surfaces. It is especially harmful because the eye is often subject to it for long enough periods of time, thus producing eye fatigue which may lead to permanent injury.

Specular reflection of a local nature frequently may be prevented by locating the light source in such a position with respect to the work that the specularly reflected light will be thrown away from, rather than toward, the eyes.

Since the brightness of a reflected image is dependent upon the brightness of the source, it follows that one remedy for reflected glare



A glass-top desk is always a potential source of glaring reflections—from glaring light sources or windows.



Half of the printed words on this page are obliterated by reflections from the glossy paper.

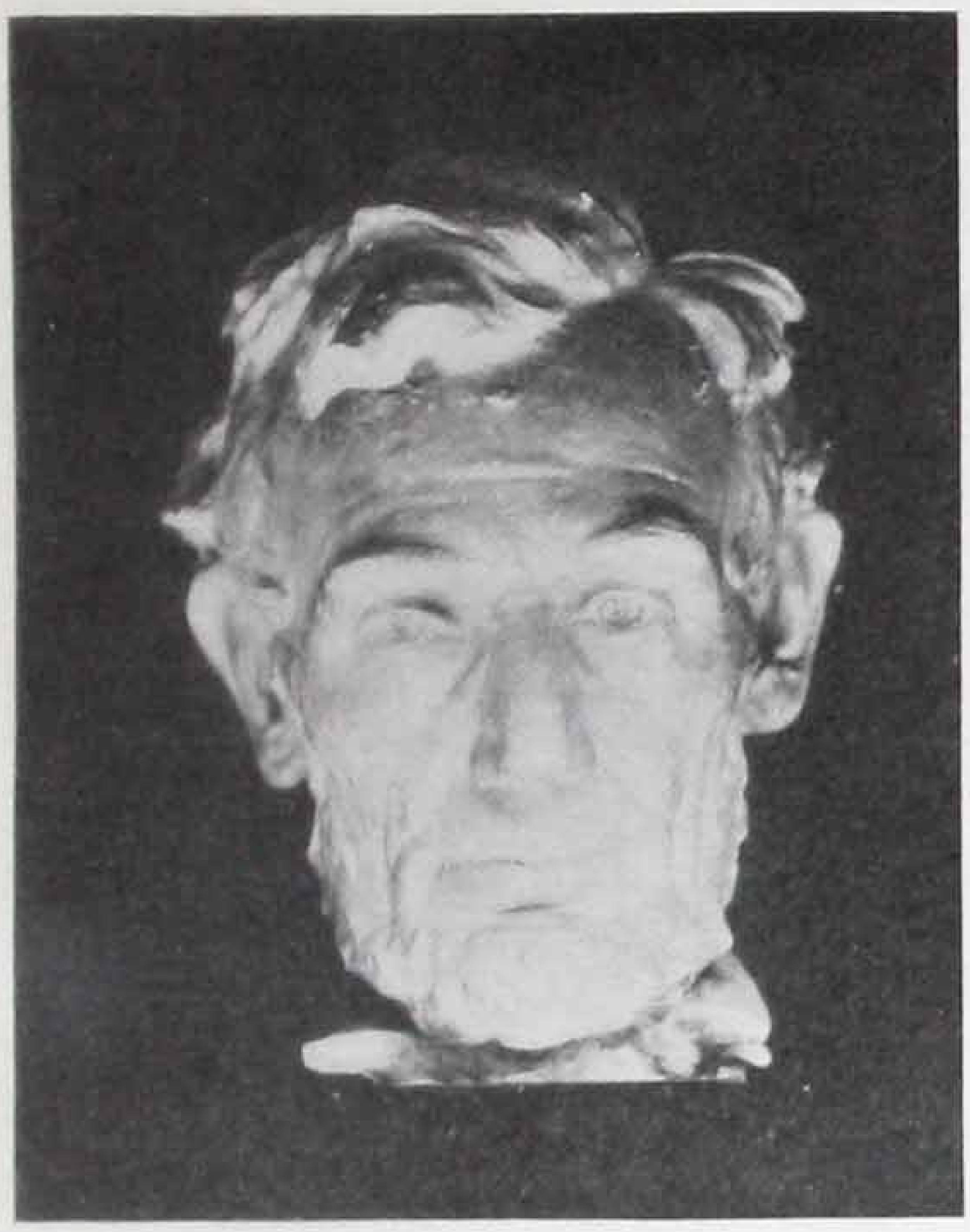
Fig. 39—Specular reflection or reflected glare

is to diffuse the light source, reducing its brightness. Sometimes this necessitates remodeling the whole lighting system—adopting new spacing for the luminaires, selecting new equipment; it may even require the installation of a false ceiling so that semi-indirect or totally indirect lighting can be used.

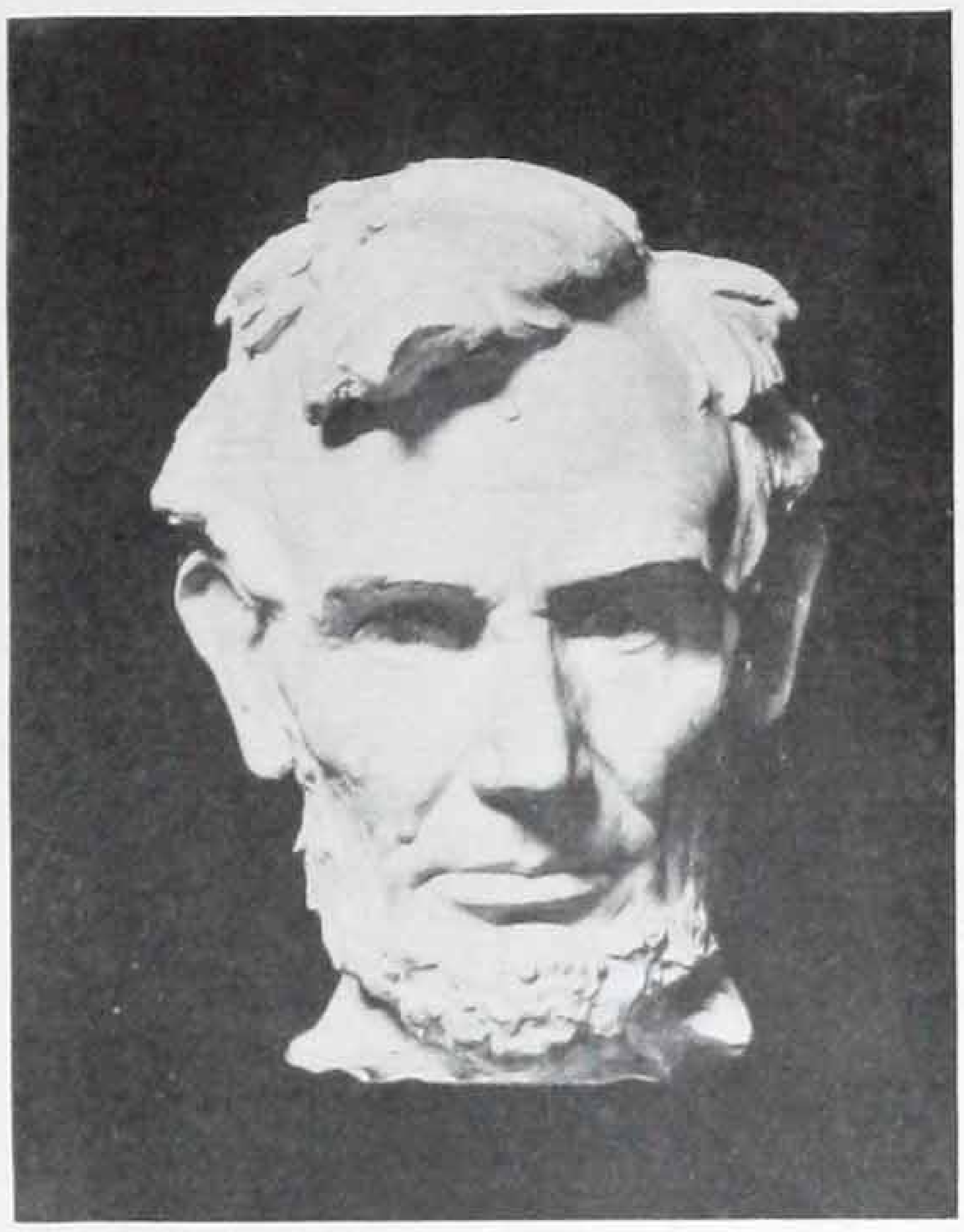
To summarize, glare depends up intrinsic brilliancy of the source, candlepower toward the eye, distance, background contrast, proximity to the line of vision, and duration of exposure.

SHADOWS

The question of shadows is important and must be given consideration if the best lighting results are to be secured. For leisure hours in the home or lounge room, shadows are restful, not unlike the long, sweeping shadows of sunset. The control of shadows in portrait photography is quite a major consideration; in the same way, when properly placed and modified, shadows may lend character to statuary or monuments in floodlighting, or in decorative interiors.



Reversed shadows give the appearance of fear, or startled surprise.



Natural shadows bring out forcefulness, kindliness, and life-like appearance.

Fig. 40—Shadows may make or mar the appearance of a floodlighted statue

The quality of general lighting obtained in a room may be quite frequently judged by the shadows which are present. Where work is being done, soft, well-illumined shadows are usually desirable since they are quite helpful in distinguishing form and detail; when shadows are sharp and black, they make objects appear harsh and unpleasant, and because such shadows may easily hide moving parts of machinery, they are often a positive danger. Dark shadows contribute also in producing a visual field of great contrast in brightness.

Fig. 41—Sharpness of shadow of the hands and the rule indicate a lighting condition annoying in an office, dangerous in an industrial plant.

Exposed lamp filaments cause harsh shadows, whereas light from a diffusing luminaire of large area tends to shine "around" an object and consequently soften the shadows. Ordinarily, luminaires should be so spaced that two or more contribute to the lighting of any point.

With general lighting, shadows from the work or fixed objects can be reduced by placing the units high, and reasonably close together. A maximum degree of shadow results in direct-lighting systems using unfrosted lamps in open reflectors of small area; a minimum, in totally indirect systems. Enclosing and semi-enclosing units produce shadows which are not as soft as those produced by indirect systems. With semi-indirect systems almost any degree of shadow can be obtained by choosing glass of the proper density.

Uniformity of Illumination

It is not uncommon to find in industrial plants that because of too great a spacing between units, some workmen are supplied with only one-half or one-third as much light as are others. Many office employees are forced to work under the same handicap; there are cases on record where the apparent incompetency of an employee, judged with respect

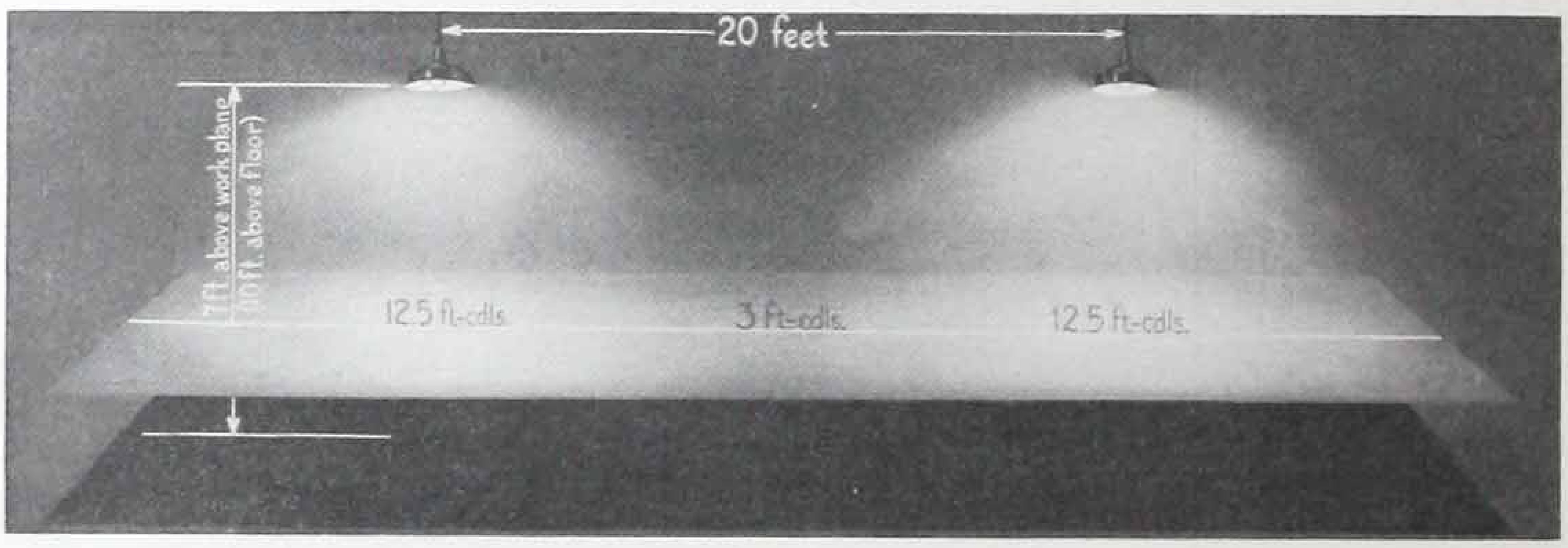


Fig. 42—Spacing between luminaires should not exceed 1½ times the mounting height above the work plane—**non-uniform lighting**—(foot-candle values based on 200-watt luminaires).

to his co-workers, has been traced to a hitherto unsuspected cause, poor lighting at his desk.

Fairly definite relations exist between the height at which lighting units are mounted above the work and the distance by which they may be separated to provide reasonably uniform illumination, with the light coming from a sufficient number of directions so that shadows will not prove troublesome. These relations have been reduced to simple tabular form for the convenience of the designer of lighting systems.*

In general, the permissible distance between units should not be more than one and one-half times the height of the light sources above

*See Bulletin 41—Illumination Design Data.

the work; closer spacing can do no harm and is often desirable, but when this spacing is exceeded, the illumination midway between units falls off rapidly.

The owner of a building should consider carefully before allowing a desire to keep initial costs low to lead to the installation of a system in which the proper spacing is not adhered to.

Illumination of Vertical Surfaces

For many locations, light is required principally on horizontal planes, such as desk tops or table tops, and it has been the custom to

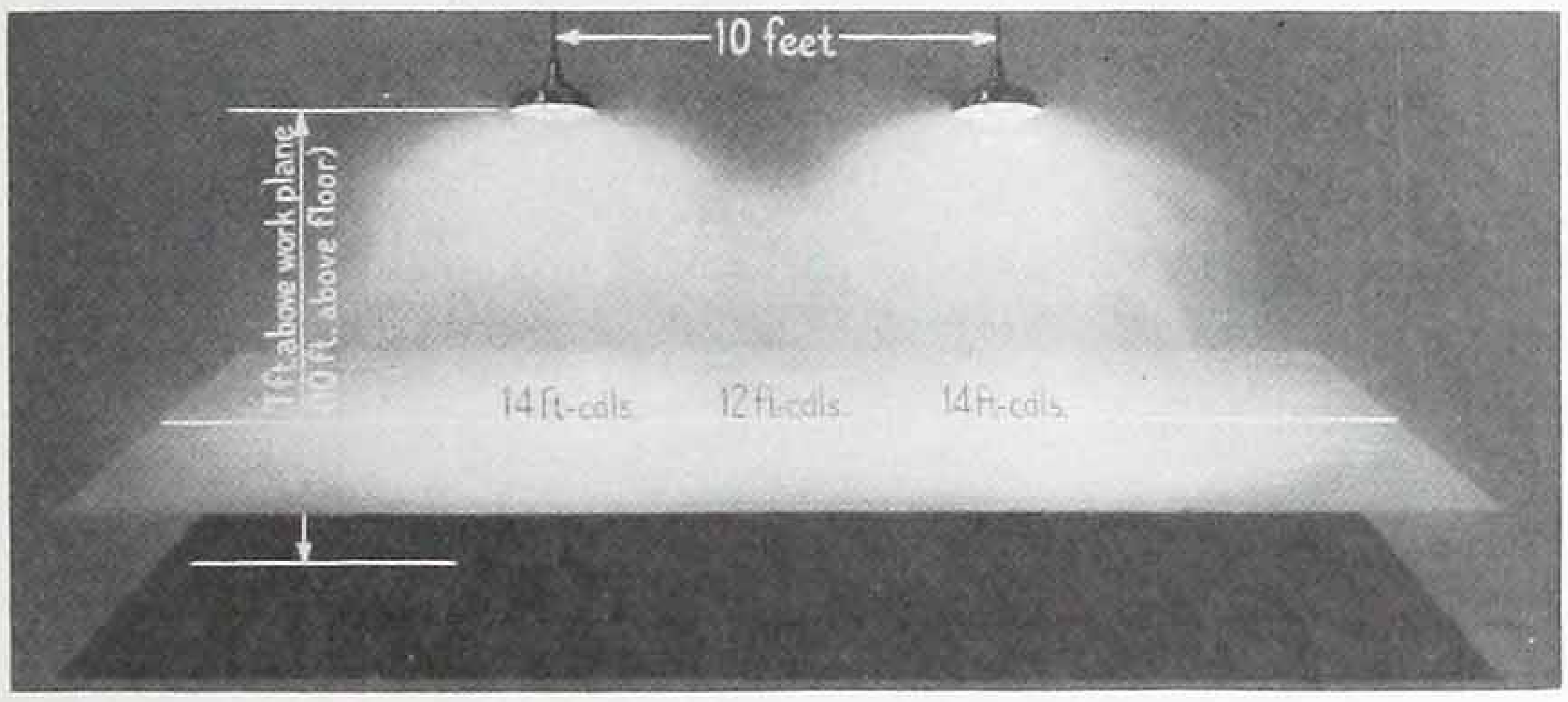
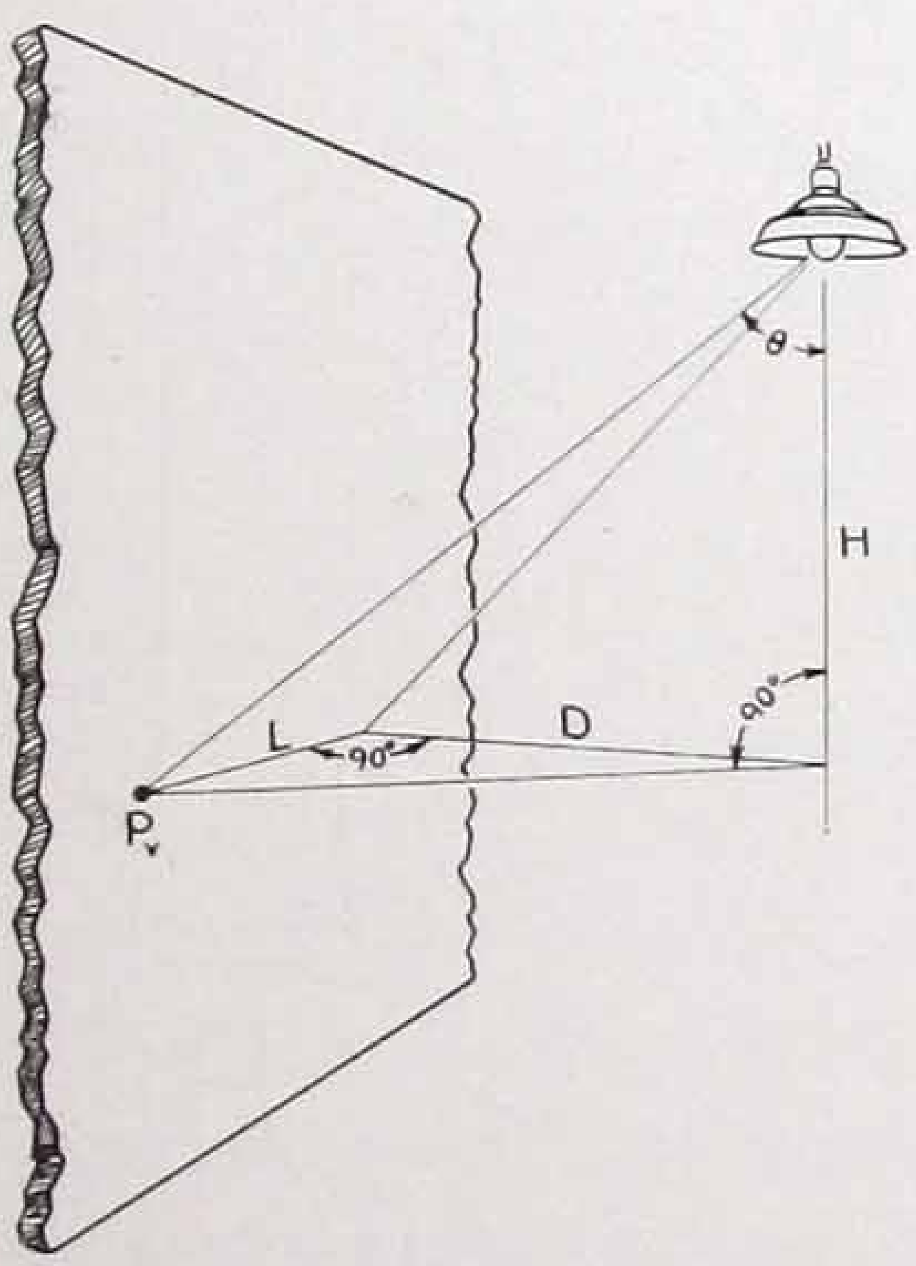


Fig. 43—Spacing between luminaires should not exceed $1\frac{1}{2}$ times the mounting height above the work plane—**uniform illumination**—(foot-candle values based on 200-watt units).

calculate illumination on the basis of the footcandlage on horizontal surfaces with the assumption that the oblique and the vertical surfaces



In calculating the illumination at the point P on a vertical surface the distance H (vertical), D (horizontal), and L (horizontal to the surface) must be known. From $\tan\theta = \frac{\sqrt{D^2 + L^2}}{H}$, the angle θ may be found. From the distribution curve of the luminaire, determine the candle-power at the angle θ (CP_θ).

Then the vertical illumination in foot-candles at P is as follows:

$$\text{Vert. Ill.} = \frac{CP_\theta \times \cos^3\theta}{H^2} \times \frac{D}{H}$$

The well known formula for horizontal illumination (foot-candles) at the same point is:

$$\text{Hor. Ill.} = \frac{CP_\theta \times \cos^3\theta}{H^2}$$

would be sufficiently lighted. Such calculations may result at times in inadequate illumination in certain planes because with ordinary luminaires the vertical illumination is only about half the horizontal.

Thus if a shop were lighted by closely-spaced automobile headlights directing the light downward from the ceiling, there would be ample light on horizontal planes but such lighting would be far from satisfactory. However, if the vertical plane illumination is of greatest importance, as in art museums, poster boards, show windows, and in some industrial applications such as automobile body painting, angle reflectors should be used, in some cases alone but usually to supplement overhead lighting.

Generally speaking, the more concentrated the distribution from overhead artificial light sources, the greater the disparity between the illumination on horizontal and vertical surfaces. Hence for general shop lighting the luminaires should have a relatively good distribution of light in the 50-70 degree zone as well as at lower angles.

Color Quality of Light

As daylight levels of illumination represent the standards which are to be sought in the artificial lighting of industrial plants, so also does the color of natural light constitute the standard which should be approached in artificial illumination. Through centuries of use, the human eye has adapted itself to function best in natural light. Natural light varies considerably in color quality throughout the day.

It might seem that the ability to see objects in their true colors is important only when, first, one is actually matching colors of materials, as in matching two pieces of silk; or second, when it is desired to see colors in their original conception, as those of an oil painting. But the fact that colors help very much, fundamentally, in the process of seeing must always be borne in mind. For example, in looking at a brass bushing on a steel machine part, the two metals, brass and steel, might have exactly the same reflection factor and they might be indistinguishable in a black-and-white photograph, or under light which does not clearly show their true colors. Since in a great many applications it is this difference in color which renders objects instantaneously recognizable to the eye, and which defines the line of demarcation between them, color discrimination is important purely from a utilitarian viewpoint. It is often considered of equal importance from the standpoint that

unnaturally-colored light creates a depressing atmosphere. In general, the color requirements of vision are satisfactorily filled by MAZDA lamps; all colors of daylight are present although the proportions are not the same. The change in the color of objects when viewed under this light is not serious.

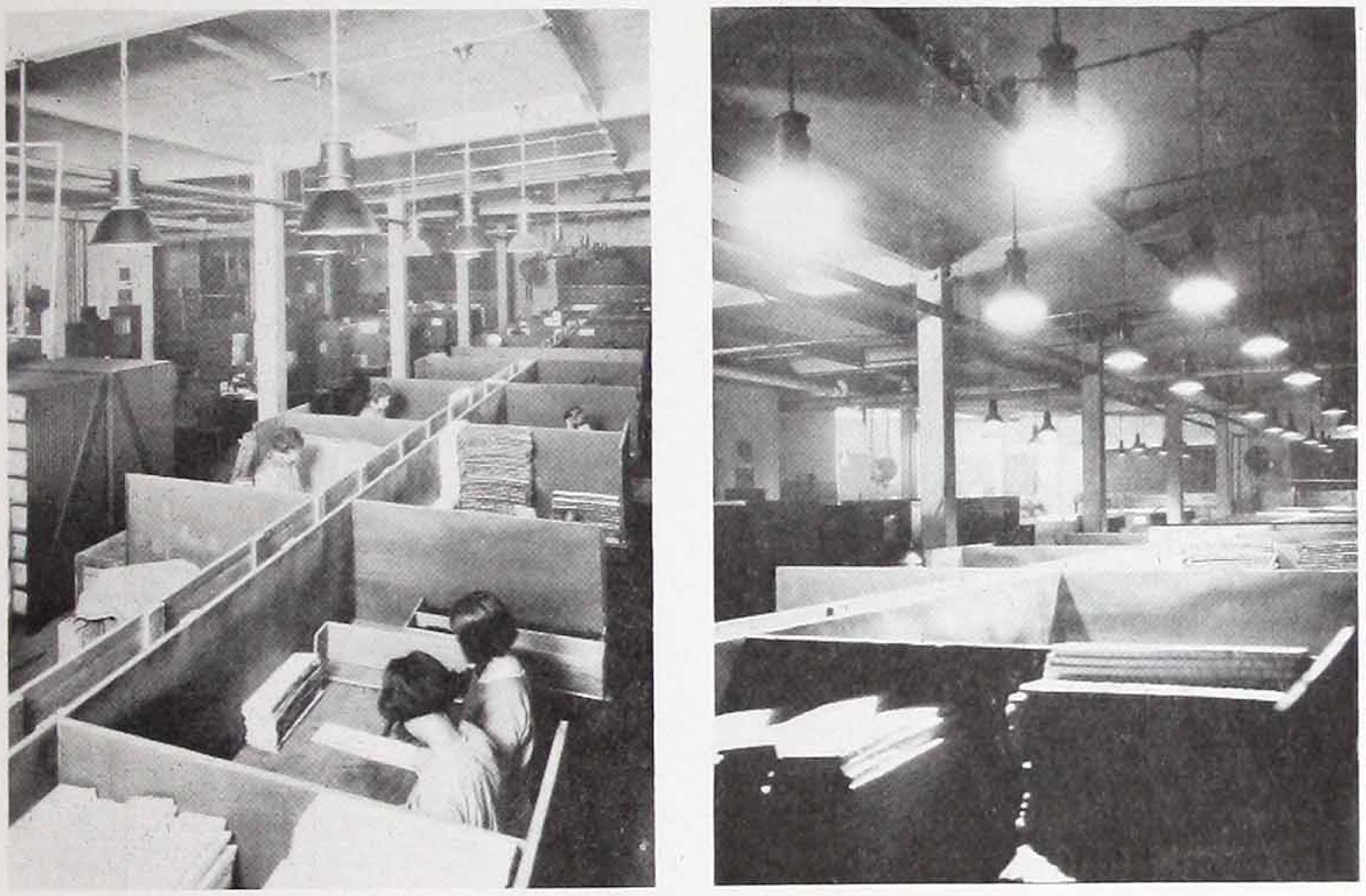


Fig. 44—Cigar sorting is done chiefly by judging by the color of the tobacco leaf. Here special color-matching units provide light of a north sky quality.

For some operations, however, work can be expedited or wares more strikingly displayed if the artificial light supplied is a closer approach to natural light. This approach may be made as close as desired: *a.* by MAZDA Daylight lamps with a blue-glass bulb which produce a light of afternoon sunlight quality (absorption about 40%); *b.* other enclosing globes of special blue glass give a close approximation of noon sunlight (absorption about 60%); *c.* for exact color-matching in the daytime, north skylight is ordinarily chosen because it is most constant, although it has considerably more blue than average daylight. Light of a north sky quality is approximated in color-matching units having special blue glass plates (absorption about 85%).

The use of MAZDA Daylight lamps is especially to be considered for applications such as show windows, clothing, fur, and rug stores, or wherever color is an element in the display of merchandise. For

industries in which the requirements are more strict, such as for lithographing, for paper, chemical and textile factories, the noon sky units are desirable when the areas to be lighted are not large. For very exact work, such as for color matching units on store counters—hosiery, jewelry, etc., the most exact north sky units should be used.

Effect of Interior Finish

The effectiveness of a lighting system depends not only upon the characteristics of the lighting unit itself, but also on the reflecting properties of the walls, ceiling, and surroundings. An installation of poor reflectors, for example, in a room with light walls and ceiling, may compare very favorably in efficiency with an installation of luminaires of good design in a room with unfavorable characteristics.

On the other hand, a large expanse of wall surface finished so light as to reflect a large volume of light into the eyes is objectionable for offices, residences, and all rooms where the occupants are likely to sit directly facing the walls. Available data indicate that where the brightness of the walls is equal to, or greater than, the brightness of white paper lying on a table or desk, annoying glare will result. With the usual types of lighting units, walls, being vertical surfaces, are not illuminated to the same high degree as desks or table tops, and walls which reflect less than 50 per cent of the light which strikes them should not produce discomfort, provided, however, that they are of a mat or unpolished finish. Walls finished in buff, light green, or gray tints reflect about the proper proportion of light and their use is generally recommended.

The color of walls and ceilings plays an important part in the efficiency of a lighting system. Semi-indirect and totally indirect systems require white or very light ceilings and upper side-walls down as low as the top of the window.

QUANTITY OF ILLUMINATION

Amount of Light or Foot-Candles Required

The eye is capable of adapting itself to see under illumination which ranges from a small fraction of a foot-candle to several thousand foot-candles. Under very low illumination the eye does not receive sufficient light to enable it to distinguish color or detail, and under unusually brilliant sunlight a blinding effect which also obliterates detail is experienced. Between these limits there is a wide range where good vision is possible.

Of all the facts regarding daylight, the most striking one is its intensity. Sunlight, on a clear day produces an intensity of six thousand to ten thousand foot-candles. Imagine, if possible, a printed page lighted, not by one, but by ten thousand candles, placed one foot from it. When such intensities are even approached in artificial lighting such as in the immediate neighborhood of a giant 30,000-watt lamp, the effect is simply scorching and the observer soon removes himself to a cooler place at a respectful distance.

Under present accepted standards, excellent lighting for industrial plants would be 20 or 30 foot-candles. Curiously enough, this sounds excessive, and looks very bright when installed. But under the open sky, unless the daylight measures one hundred foot-candles or more, one gets the impression of a very dull day indeed.

It may be concluded that it is certainly too soon to be anxious about the effect that artificial light is having upon the eyes purely by reason of its intensity, when proper precautions are taken to insure good diffusion.

If the illumination is safeguarded as regards quality, that is, well diffused and with no extreme brightness contrasts between the surface to be looked at and its surroundings, it is difficult indeed to provide too much light for the eye. Some comparisons of illumination levels are illustrated in the frontispiece.

Considerations of economy usually limit the level of illumination employed in artificial lighting to the lower values. So closely is the lower limit approached that it is necessary in planning a lighting installation to take into consideration such factors as the color of objects to be illuminated—for objects are seen by the light which

they reflect, and dark objects require higher intensities than light-colored ones for equally good vision—the order of brightness of surroundings, the intricacy of the work to be performed under artificial lighting, and the amount which is considered expedient to apportion to the advertising value of an attractively lighted interior.

The increases in production, decreases in spoilage, and the reduction in the number of accidents, accompanying the introduction of higher levels of illumination in industrial plants, are accredited to better visual conditions. Under higher levels of illumination the eye has been shown to respond accordingly, by: (1) increased ability of perception (Fig. 45); (2) increased speed of discrimination or rapidity with which the eye is able to identify a difference or differences in objects (Fig. 46); (3) increased accommodation, or the ability of the eye to focus upon objects at different distances; (4) improvement in sustained vision, or the ability of the eye to keep a clear view of all details of an object under continuous observation; and (5) increased speed of vision or speed of reading, as shown by Fig. 47.

Inasmuch as the eyes are almost continually on duty, shifting about and changing focus, the muscles and nerve centers account for an enormous amount of energy in the course of a day's work. Hence it becomes important that the lighting shall be such as to make possible

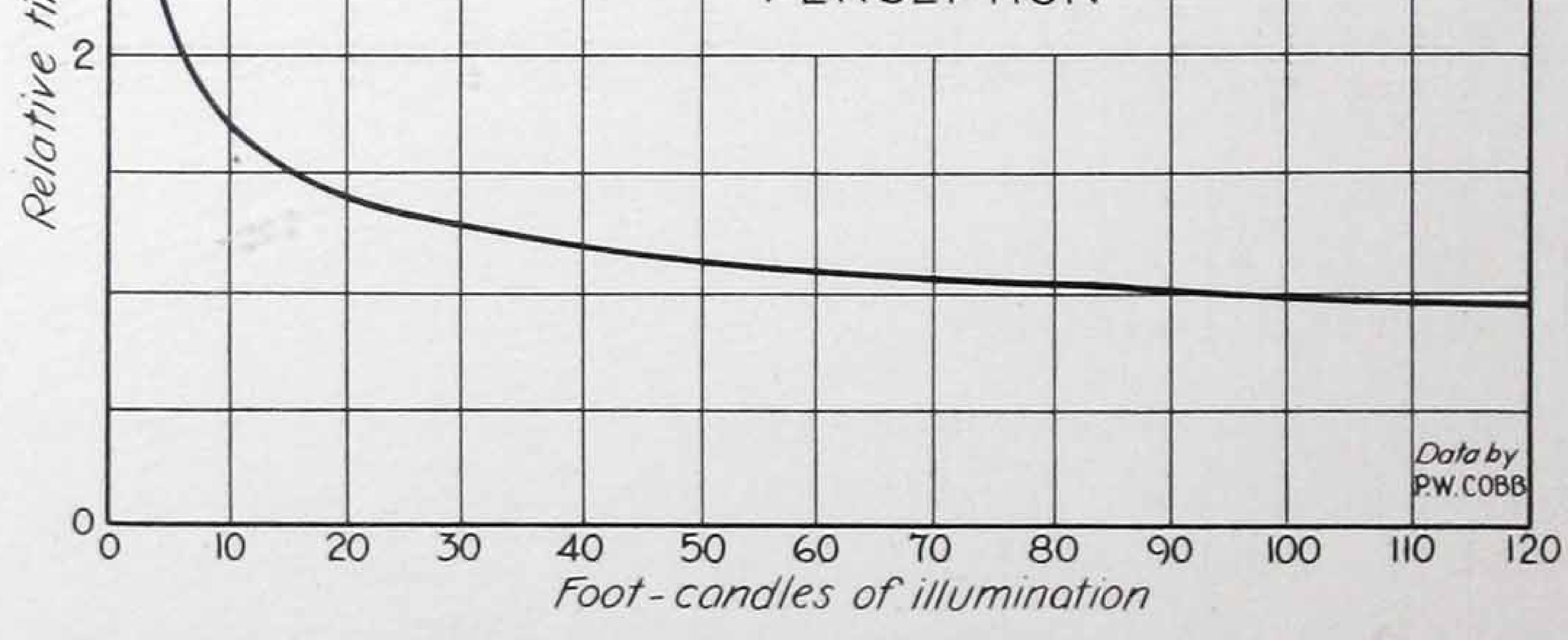


Fig. 45—It takes 3½ times as long for the eye to perceive a small test object under 2 foot-candles as it does under 100 foot-candles

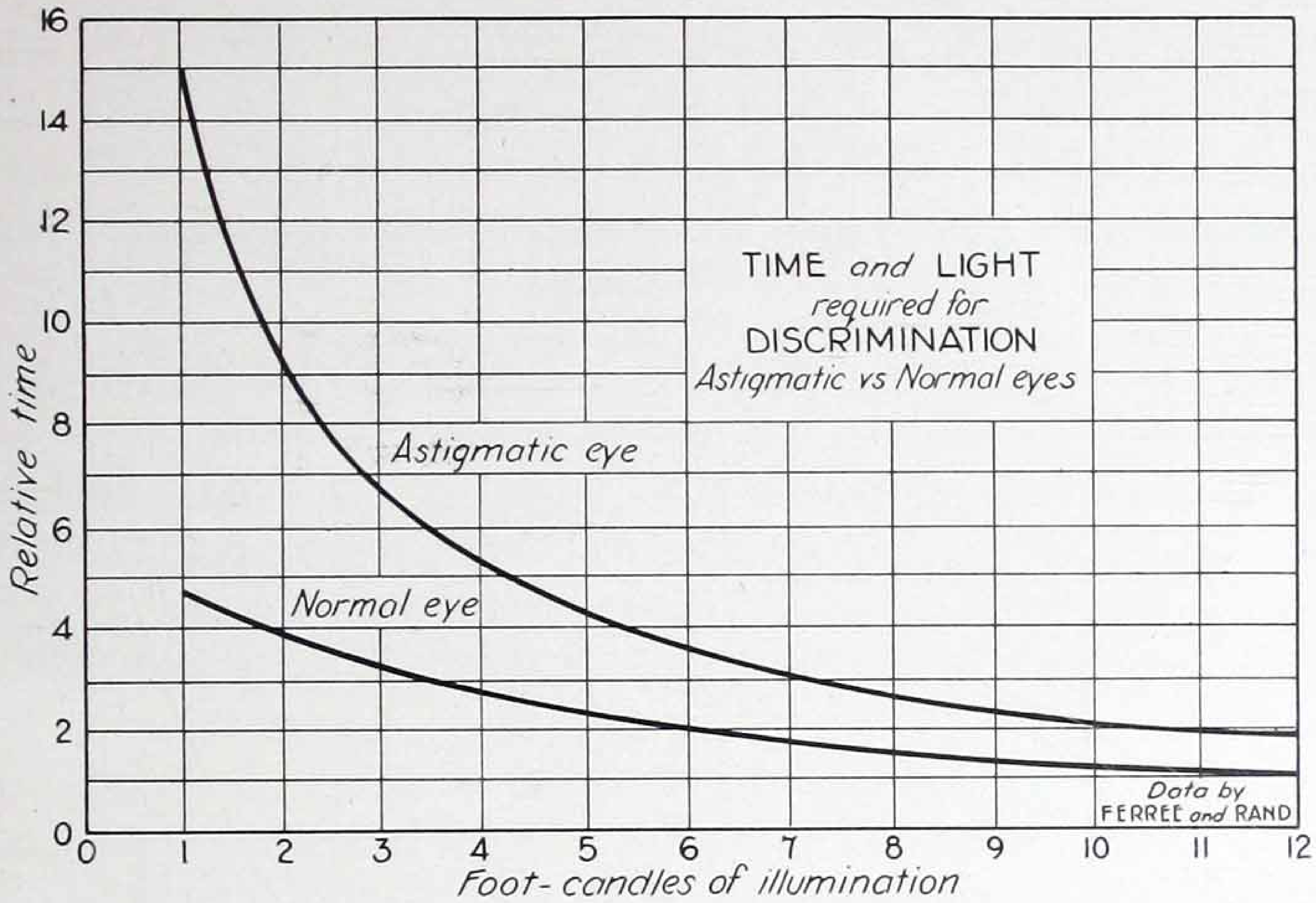


Fig. 46—Normal eyes increase in speed of discrimination 3½ to 1 between 1 and 12 foot-candles; astigmatic eyes show even more pronounced improvement.

an effective impression upon the retina with the least strain or handicap. When the illumination is of a low order, these impressions will be inadequate, the eye muscles have extra work thrown upon them and they become rapidly exhausted; work is consequently retarded and mistakes are frequent.

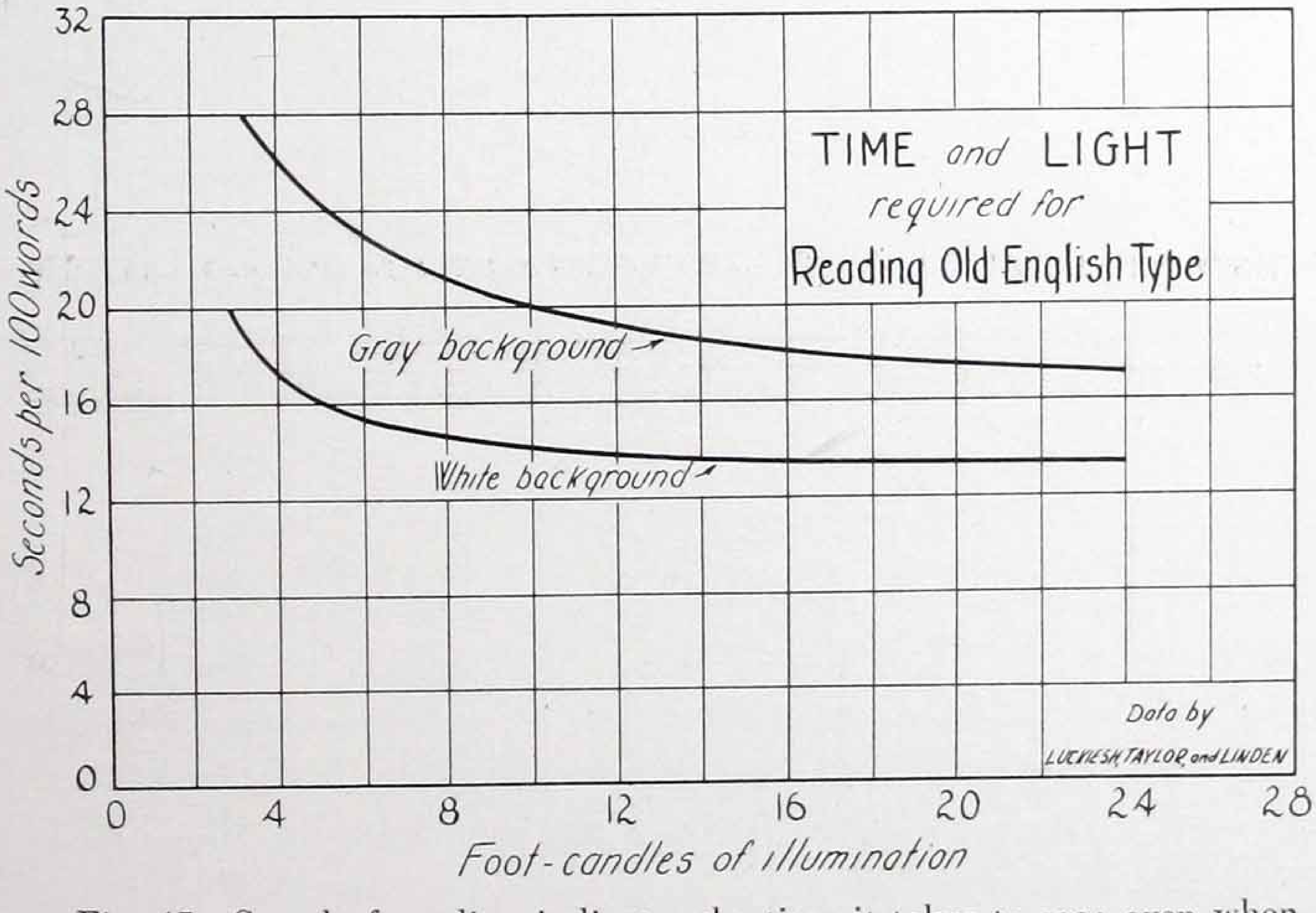


Fig. 47—Speed of reading indicates the time it takes to see; even when conditions for reading are best, i. e., black and white contrast, the eye can see 20% more quickly under good illumination.

In most of the tests mentioned above it was shown that the astigmatic or subnormal eye is helped more by improvements in illumination than the normal eye. Tests of several thousand employees in factories and commercial establishments show that more than 50 per cent of the employees have uncorrected faulty vision.

Complete tables of recommended standards of illumination* have been established by experience and are used by various authorities as standard in current practice and are given as a guide for different classes of work. Bearing in mind the character of the work, the fineness of detail to be observed, one should be able to select from the range of values given, the degree of illumination that would be considered suitable. In show window lighting, street lighting, floodlighting, and similar types, recommended practice is governed also by the location of the place to be lighted, and the standard of illumination of the immediate surroundings.

CHOICE OF LIGHTING SYSTEM

As previously mentioned, there are three general systems of illumination classified according to the manner in which the light is distributed:

1—Direct lighting
2—Indirect lighting
3—Semi-indirect lighting

Direct lighting systems employ luminaires which send the greater portion of light direct to the surfaces to be illuminated. Both open reflectors and enclosing glassware come under this heading. Enclosing glassware is particularly applicable and desirable since it diffuses the direct rays of the lamp, improves the diffusion somewhat, and greatly improves the appearance of the lighted room.

Formerly, open reflectors, both glass and metal, were the most common types of luminaires. With the advent of more powerful sources, the use of open-type glass reflectors has largely been discontinued. Open type metal reflectors, however, especially those of porcelain enamel, are being used successfully in the industrial lighting field.

*Refer to Bulletin 41—Illumination Design Data.

Porcelain-enamel reflectors are commonly classified by shape as dome or bowl, the former being generally more desirable because of better illumination of vertical surfaces, and higher efficiency.

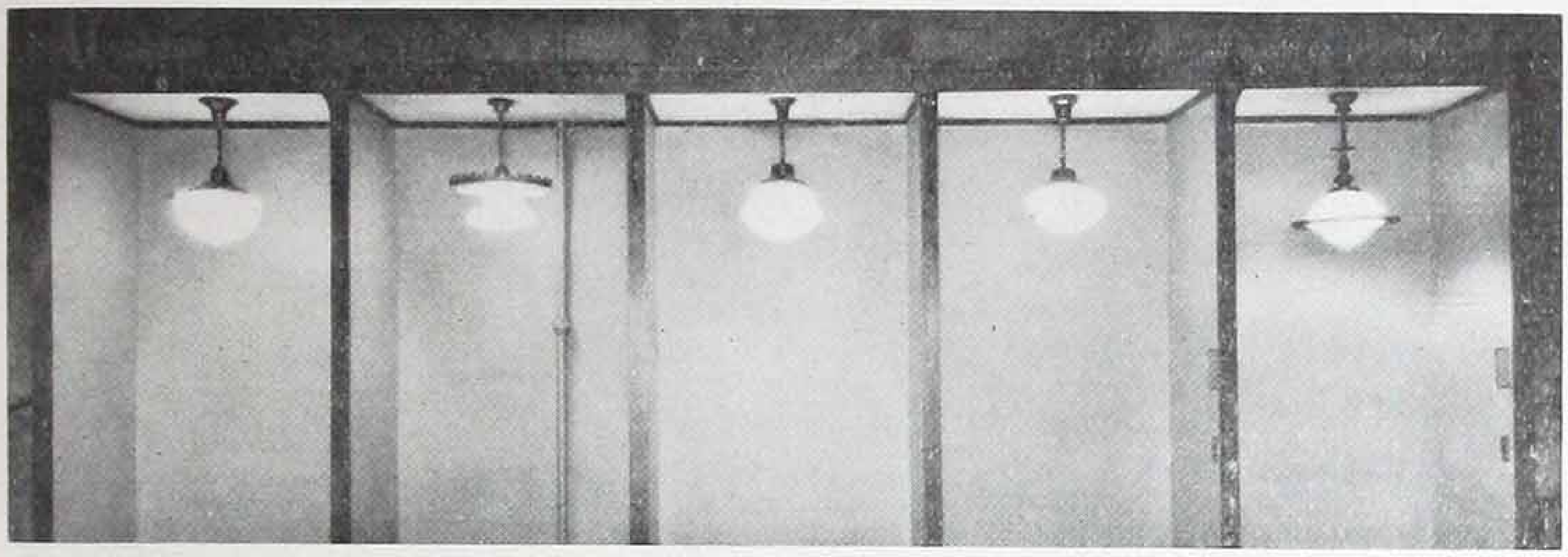
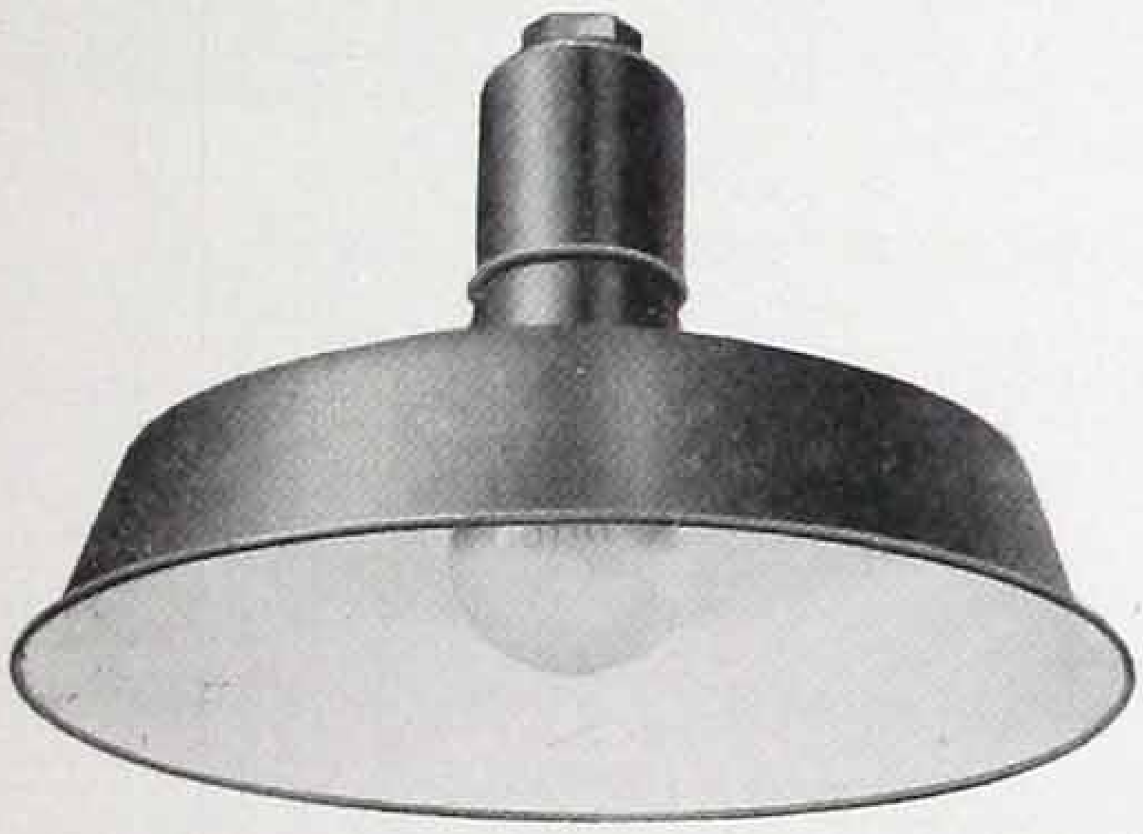


Fig. 48—Direct lighting luminaires

The dome reflector shown in Fig. 49 is the R L M (Reflector and Lamp Manufacturers') Standard Dome.* Manufacturers of this reflector must comply with standard specifications of contour and quality of the reflecting surface. This insures a durable and highly efficient luminaire,



R L M Standard Dome with white-bowl lamp†

Glassteel Diffuser with clear lamp

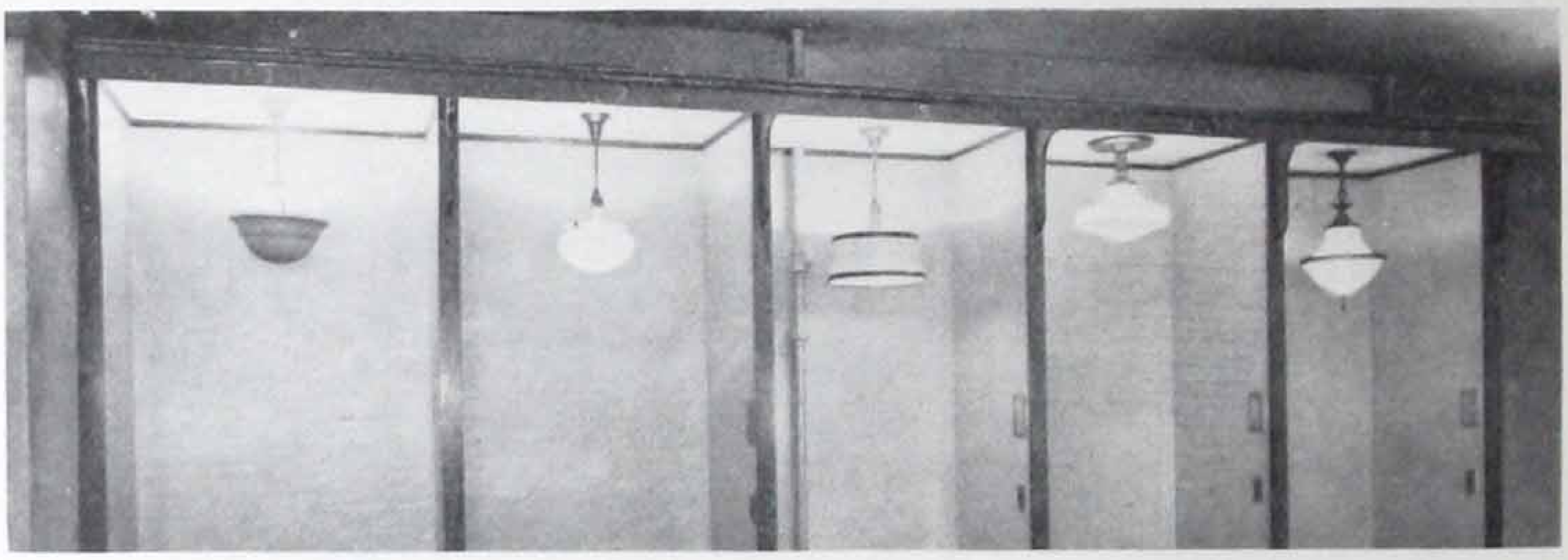
Fig. 49—Types of porcelain-enamel steel reflectors

a contour of reflector which will insure an effective light distribution, and a depth which will shield the filament from view sufficiently to minimize glare.

*The specifications for the minimum diameters for each size of reflector provide for a large reflecting surface. Diameters for reflectors used with 50, 60, and 100-watt inside-frost lamps are 12 inches; 100-watt inside-frost lamps, when used with socket extensions, 14 inches; 150-watt, 14 inches; 200-watt, 16 inches; 300 and 500-watt, 18 inches; 750 and 1000-watt, 20 inches. The reflectors are so proportioned that when used with these standard lamps the angle of cutoff of view of the filament is 72½ degrees from the vertical axis. The contour of the reflector is such as to avoid undue concentration of light directly beneath the unit; output is approximately 75 per cent of the generated light.

†At mounting heights of less than 20 feet, R L M Domes should be equipped with a white-bowl or diffusing-bulb lamp.

The Glassteel Diffuser (Fig. 49) is a combination of the dome reflector and a white-glass luminaire. The downward rays of light are diffused by the white-glass globe which completely encloses the lamp. Slots in the top of the reflector allow a small part of the light to be emitted upward, thus partially illuminating the ceiling and generally improving the appearance of the lighted room. The reflector also reduces glare by hiding a large part of the bright area of the globe. For industrial plants where a high quality of illumination is desired, the Glassteel Diffuser is usually recommended.



←— Indirect —→ ←— Semi-Indirect —→

Fig. 50—Semi-indirect and totally indirect lighting luminaires

Indirect lighting utilizes the ceiling and upper sidewalls for the redirection and diffusion of all the light emitted by the luminaires. Since the ceiling acts as the light source, with the maximum of distribution directly downward, glare from the unit is avoided, and shadows are soft, but for a given footcandlage on horizontal surfaces there is usually somewhat less illumination on vertical surfaces than with other systems. The most efficient luminaires of this type employ a mirrored glass reflector within the bowl to direct the light to the ceiling.

Semi-indirect lighting furnishes a means of combining the features of direct and indirect systems. With a correctly designed bowl of white glass, brightness of the unit is low enough so that eye fatigue is avoided, and sufficiently direct light is emitted so that the proper degree of vertical illumination, and soft or graded shadows are produced. As has been previously noted, a light-density white glass may be used in certain locations where the luminaires are hung high and the nature of the

work is such that the units are not in the usual range of vision. There is no marked difference in lighting effect between a very light-density semi-indirect unit and the usual direct lighting enclosing luminaire, but in general a unit which directs more than 50 per cent of the light upward is classed as semi-indirect. The better units, however, are of sufficient density so that not more than 20 per cent of the light is transmitted through the bowl.

The individual characteristics of the room to be lighted are important factors in the selection of a lighting system. The presence of large quantities of dust often discourages even a consideration of indirect or semi-indirect systems unless these units are enclosed at the top. The dark tone of the walls and ceilings in factories also often preclude the use of other than a system of direct lighting. Cost and efficiency are factors which may limit the choice, although the present tendency, particularly in the more specialized branches, is to make good lighting the first consideration. It may also be mentioned that the liberal use of paint or whitewash can hardly be too strongly recommended.

In residence, office, and public-building lighting, the system should, of course, be of good appearance and in harmonious relations with the decorative or architectural features of the surroundings. Semi-indirect and enclosing luminaires lend themselves most readily to these classes of service if the color of the ceiling and walls permit their use. It should always be borne in mind that such luminaires to be satisfactory as to glare must be selected with care in accordance with the suggestions previously outlined. Totally indirect units are practically certain to be satisfactory from the glare standpoint.

When the installation is such that a decorative luminaire is essential, it should always be remembered that the primary purpose of the luminaire is to provide light of sufficient quality and quantity to meet the visual requirements. Luminaires, no matter how beautiful or artistic, are unacceptable unless the lighting requirements are satisfied. Luminaire design should and can easily incorporate highly artistic motifs, with an equal high regard for their function as efficient lighting devices.

LOCATION OF LIGHTING UNITS*

For anyone who is installing the system and estimating its cost, or who is responsible for the results, the location of the outlets and the current-carrying capacity of the wiring are of first importance. The cost of installing a lighting system is largely made up of wiring cost; therefore, it is imperative that the wiring be adequate, because when the outlets are once properly installed as to spacing and size of wire, a change in type of reflector or in the size of lamp may be made without undue complication, but where the spacing of outlets is too great or the wiring is inadequate, satisfactory results can never be obtained without considerable alteration.

Spacing of Luminaires

As has been previously mentioned, the spacing between units in relation to their height determines the degree of uniformity of illumination and influences greatly the degree of shadows which result.

In many cases the construction of a building divides it into a number of bays, and, for the sake of appearance, the units should usually be placed symmetrically in these bays if compatible with uniformity of illumination. Panel designs on the ceiling, or other decorative features, also call for a symmetrical spacing, but it must always fall within the limits of maximum permissible spacing with regard to the height of the units above the working plane if uniformity is desired. When there are no natural divisions in the room, and the outlets are not already placed, the room should be divided into a number of areas approximately square, and the units placed at the center of each, the maximum distance between units not exceeding 1½ times their height above the plane of work, which in most cases corresponds to a spacing about equal to the mounting height above the floor. With such a system the distance from the nearest row of outlets to the wall is one-half the spacing distance; the distance from the walls may necessarily be made less than half the spacing distance in order to avoid shadows and to maintain high footcandlage close to the walls, where there are desks or benches close to the walls.

Factors Influencing Size of Lamp Required

Having desided upon the desired number of foot-candles, the total number of lumens which must be supplied at the working level is equal

*See also Bulletin 41—Illumination Design Data, and other bulletins listed on back cover.

to the foot-candles desired multiplied by the area of the space in square feet to be lighted. The lamps must, however, emit a greater number of lumens than this, for not all of the light generated reaches the plane of the work; some of it is absorbed in the reflector or diffusing accessories; part of it strikes the walls and ceilings and of this, part is absorbed and only a portion is reflected to the work. The amount lost depends upon the characteristics of the lighting unit, the finish of the walls and the ceiling, and the proportions of the room.

Room Index

In order to understand the effect of room proportions and the mounting height of the units on the resultant illumination, consider a room 40 ft. x 40 ft. with dark walls equipped with two systems of lighting which are identical except that in one the luminaires are 10 ft. above the floor and the other, 14 ft. It will be readily seen that a higher level of illumination will result in the case of the lower mounting height because with the same amount of light starting downward

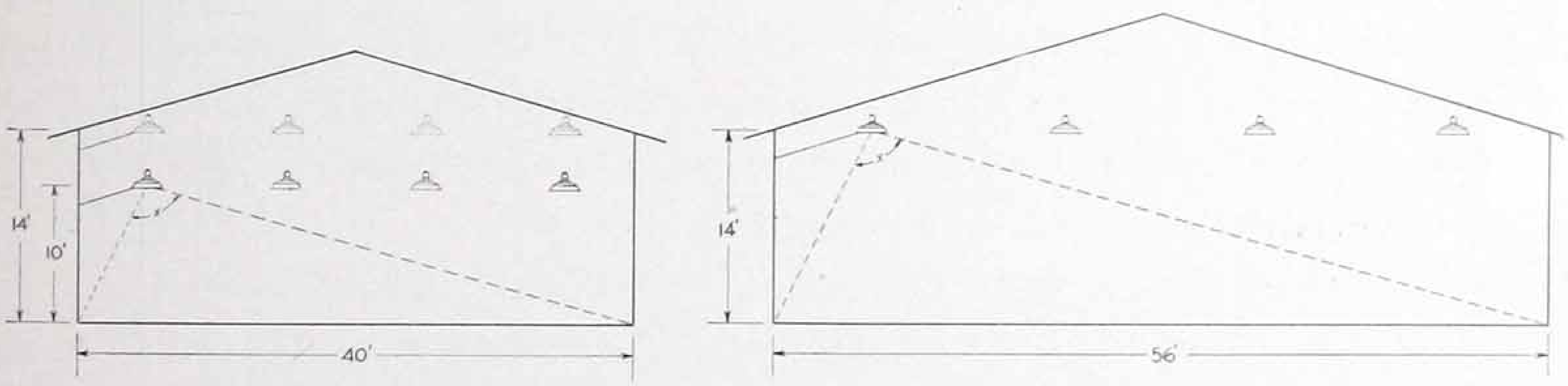


Fig. 51—The uniformity and amount of illumination on the working plane is not changed if the room proportions remain the same

there is less light in proportion which strikes the walls and a higher proportion striking the working surfaces.

The fact that in one case the units are farther from the working plane in itself has no influence upon the percentage of light utilized. It is the proportions of the room not the actual distances that count. As seen in Fig. 51, a mounting height of 10 ft. in a room 40 ft. x 40 ft. is exactly the same as far as efficiency is concerned as a room 56 ft. x 56 ft. with a mounting height of 14 ft.

The shape and size of the room, for a fixed mounting height, is likewise important with reference to the proportion of light which strikes the side-walls materially affecting the foot-candles on the horizontal working plane. For example, if in a room 40 ft. x 40 ft. and

another 80 ft. x 20 ft. with the same ceiling height, the proportion of wall area in the latter is considerably greater than in the case of the 40 ft. x 40 ft. room, although the floor area is the same in both cases. Similarly, the proportion of wall area to floor area in a large room is less than in a small room of similar shape, consequently there is a comparatively higher utilization of light in large rooms for equal mounting heights.

It is not, however, desirable to keep all light off the side-walls as a certain amount is necessary to reduce brightness contrasts, to prevent a tunnel-like appearnace of the room, and to give it a generally cheerful atmosphere.

Coefficients of Utilization

The proportion of the lumens generated by the lamps which reaches the plane of work is know as the Coefficient of Utilization.* It is dependent upon the type of diffusing and reflecting equipment, the color of walls and ceiling, and also upon the proportions of the room.

Certain types of reflectors due to their contour and quality of materials will direct light more efficiently to the work than will other types. With open type enameled-steel reflectors the influence of color of walls and ceiling is at a minimum; the effect of this factor becomes of increasing importance, considering in turn—open glass reflectors, enclosing light-directing, and simple diffusing units, becoming of major importance with semi-direct and indirect types.

Allowance for Depreciation

In addition to increasing the total lumens provided by the lamps to compensate for losses in utilization, allowance must be made initially for the inherent depreciation in lumen output of the lamps and in reflecting efficiency of the reflector, walls, and ceiling due to deterioration and to the collection of dust and dirt. Installations fall in efficiency so that their average values is from 15% to 50% less than the initial, depending upon the type of reflector and local conditions of smoke and dust.

$$\text{Lamp Lumens Required per Outlet} = \frac{\text{Floor Area (sq. ft.)} \times \text{Desired Foot-candles}}{\text{No. Outlets} \times \text{Coeff. of Utilization} \times \text{Depreciation Factor}\dagger}$$

*See Bulletin 41—Illumination Design Data.

†Depreciation Factor—Usually .75 for fairly clear locations, .70 for average, and .65 for dirty locations or where cleaning is infrequent.

BULLETINS OF THE NATIONAL LAMP WORKS

The purpose of the series of bulletins published by the National Lamp Works of General Electric Company is to supply authoritative information on artificial lighting. A number of typical bulletins selected from the series are listed below.

41D—Illumination Design Data

This bulletin presents a simple method of illumination design adapted to general lighting systems where standard equipment is to be used. Charts and tables simplify the method and make for accuracy in the design.—24 pages.

42A—Factory Lighting Designs

Ready-made illumination plans for the more common bay sizes found in industrial interiors are presented in this bulletin.—48 pages.

45A—Lighting Designs for Stores

Presents lighting recipes for a number of typical store interiors, both large and small, together with designs and notes on lighting of the display windows.—48 pages.

46A—Street Lighting Designs

Urges that all cities outline a complete plan and proceed year to year with an orderly development of a street lighting program. Simple recipes are given for the lighting of business, thoroughfare, and residence streets for cities of various sizes.—20 pages.

47—Home Lighting Fundamentals

A practical guide for lighting the home, replete with sketches illustrating the use of various types of lighting fixtures to obtain desirable lighting effects in the different rooms.—32 pages.

49—Lighting the Motor Bus

This bulletin discusses the lighting of the bus interior, the electrical circuits, and various exterior lighting units—headlights, tail-lights, signals, markers, etc.—24 pages.

50—Electrical Advertising—Its Forms, Characteristics, and Design

This bulletin contains a discussion of the requirements, characteristics, and adaptabilities of the principal forms of electrical advertising, simple approximate rules to guide the sign user and builder, and many new ideas in picture and story for those interested in this most rapidly growing publicity medium. —48 pages.

51—Night Lighting for Outdoor Sports

This bulletin discusses the various types of equipment and gives comprehensive lighting plans for tennis, volley ball, race tracks, bathing beaches, and a number of other common outdoor recreations.—24 pages.

In addition to the bulletins listed above, publications are available on various subjects such as motion picture projection, lamp temperatures, automobile headlighting, school lighting, and other subjects of general interest to the lighting industry.

Those requesting bulletins are asked to state the subjects in which they are interested.

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